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(12) **United States Patent** (10) **Patent No.:** **US 10,987,154 B2**
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(54) **ELECTROSURGICAL GENERATORS AND SENSORS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 98 days.

This patent is subject to a terminal disclaimer.

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Related U.S. Application Data

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(51) **Int. Cl.**
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    A61B 18/14   (2006.01)
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    CPC *A61B 18/1233* (2013.01); *A61B 18/1445* (2013.01); *A61B 18/1477* (2013.01);
        (Continued)

(58) **Field of Classification Search**
    CPC G01R 15/181; A61B 18/1233
    See application file for complete search history.

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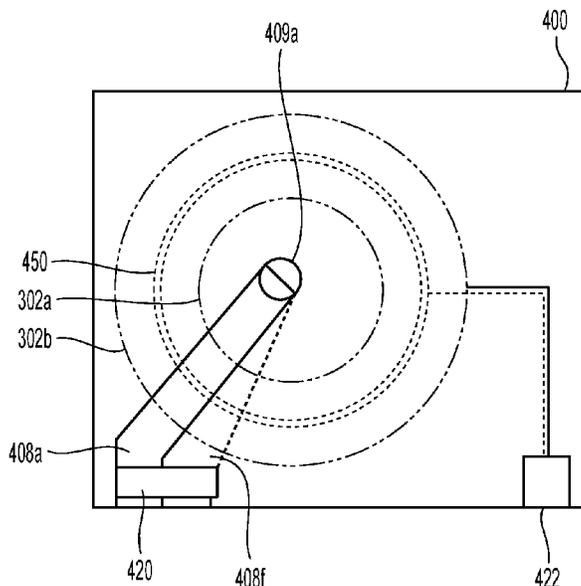*Primary Examiner* — Lee E Rodak
Assistant Examiner — Adam S Clarke
(74) *Attorney, Agent, or Firm* — Carter, DeLuca & Farrell LLP

(57)   **ABSTRACT**

An electrosurgical generator includes a radio frequency output stage configured to output at least one radio frequency waveform and a sensor for sensing current. The sensor includes a current sensor coil having: an outer coil, an inner coil coupled to and disposed within the outer coil, and at least one shielding member disposed over the outer coil. Each of the at least one shielding member and the outer coil define an opening therethrough. The generator also includes at least one active lead coupled to the radio frequency output stage and passing through the current sensor coil. The current sensor coil is configured to output a signal indicative of a current within the at least one active lead.

20 Claims, 21 Drawing Sheets

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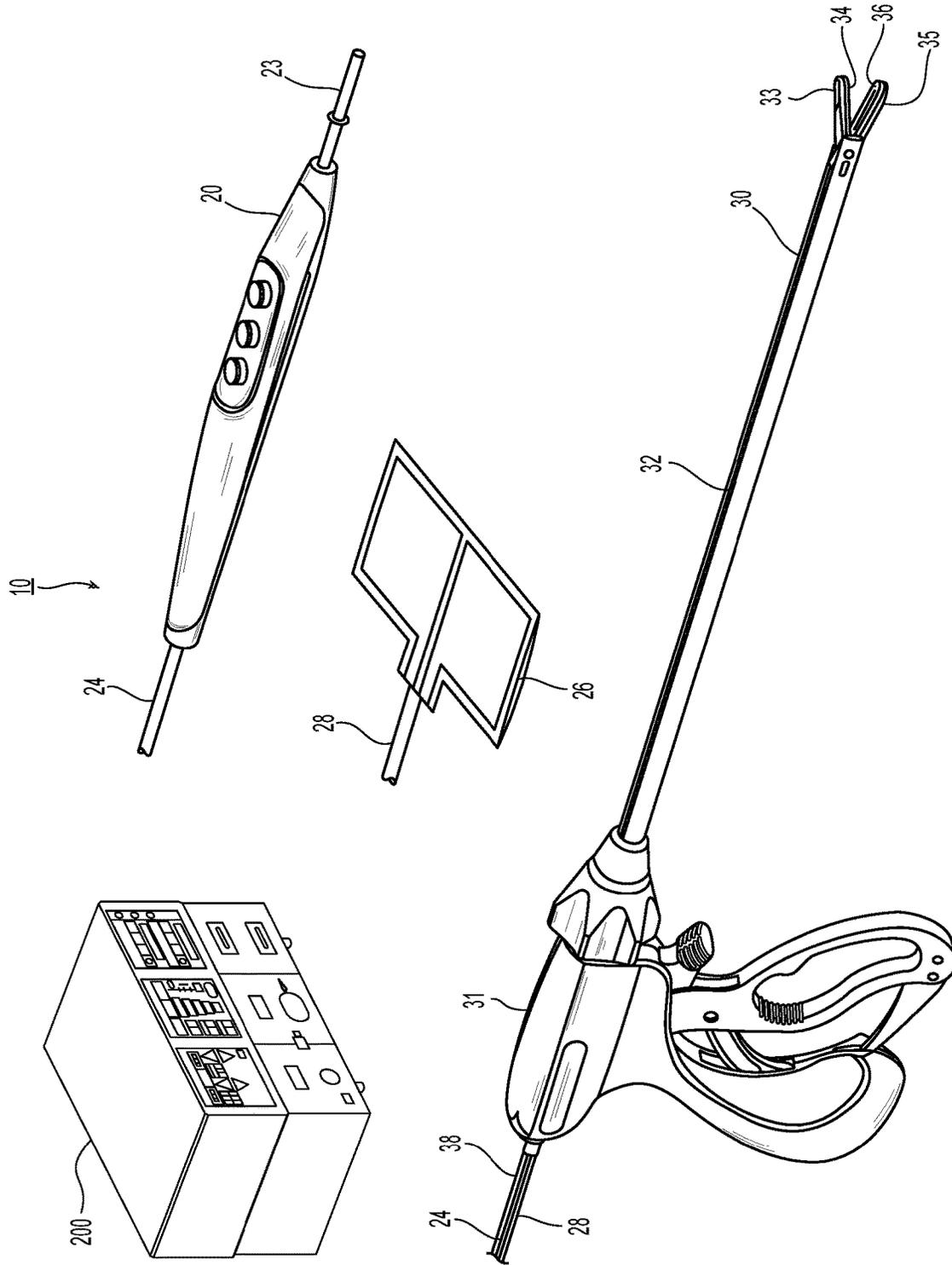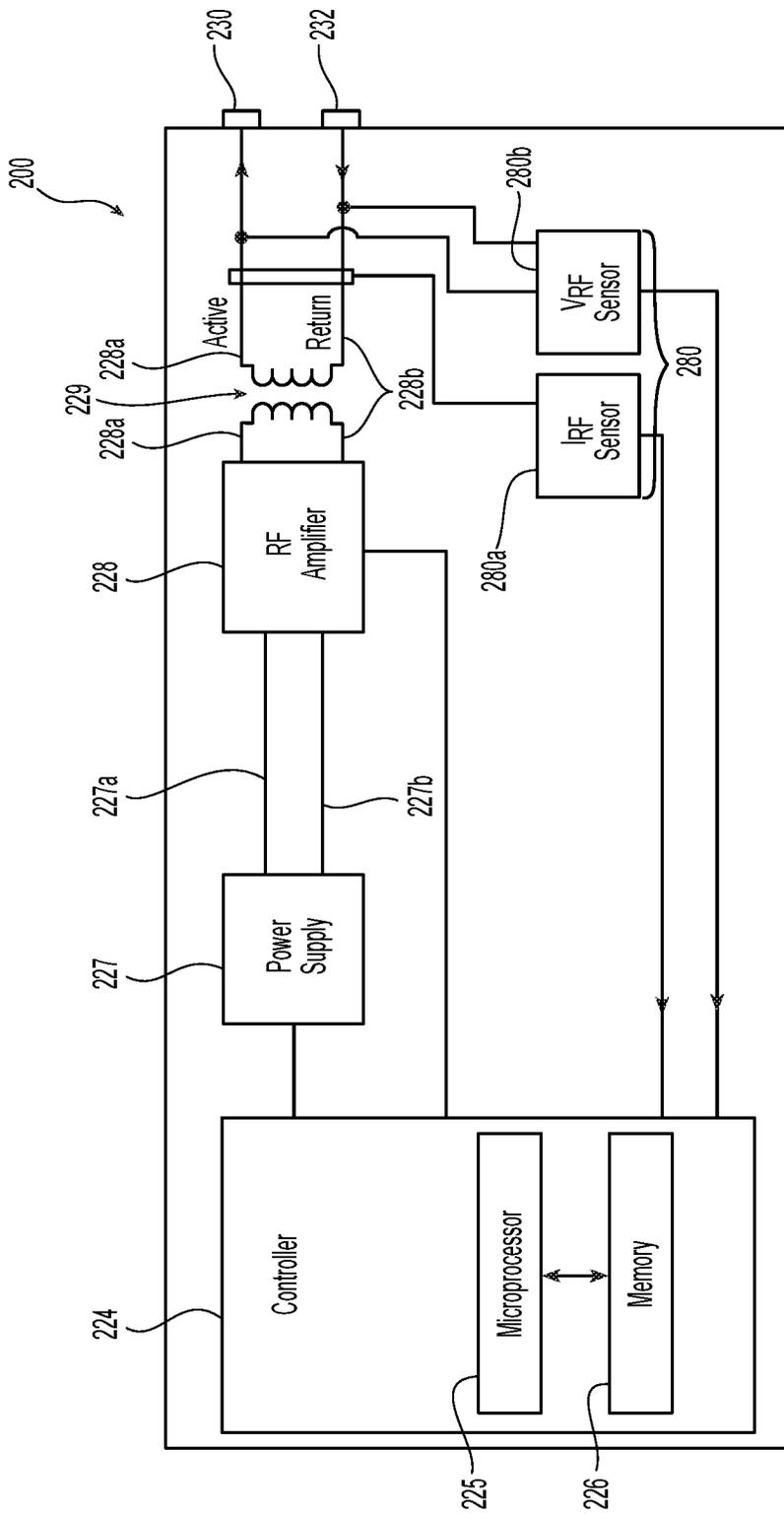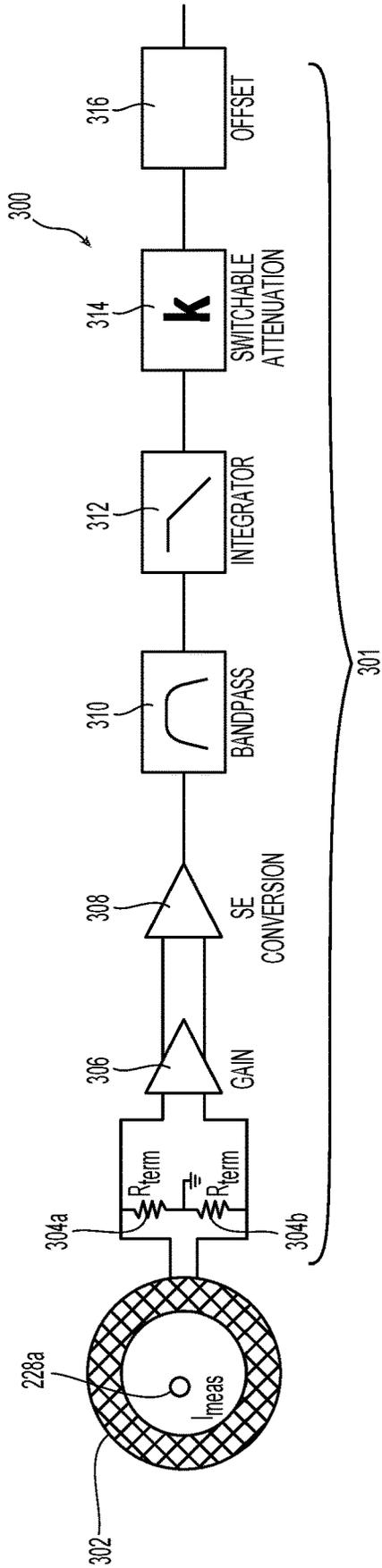
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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

400

409b 409a

408a   404a

408b

404b

408c

405 {   404c

408d

404d

408e
408f   404e

Fig. 8

409a   400

450
302a
302b

408a

420   408f   422

Fig. 9

Fig. 10

Fig. 11

Fig. 12

311

V_{IN} R_1 R_2 C_2 311e 311a

C_1 311c 311d

311b

V_{OUT}

R_3 311f

R_4 311g

Fig. 13

312

312a

V_{OUT}

C

312e

312c R_1 R_2 312d

312b

Fig. 14

Fig. 15

$$V_{SIGNAL} \; \alpha \; I_{DM} + I_{CM}$$

I_{DM}

228a

I_{CM}

228

228b

I_{DM}

600

I_{CM}

Fig. 16

$$V_{SIGNAL} \; \alpha \; 2 \; X \; I_{DM}$$

I_{DM}

228a

I_{CM}

228

228b

I_{DM}

600

I_{CM}
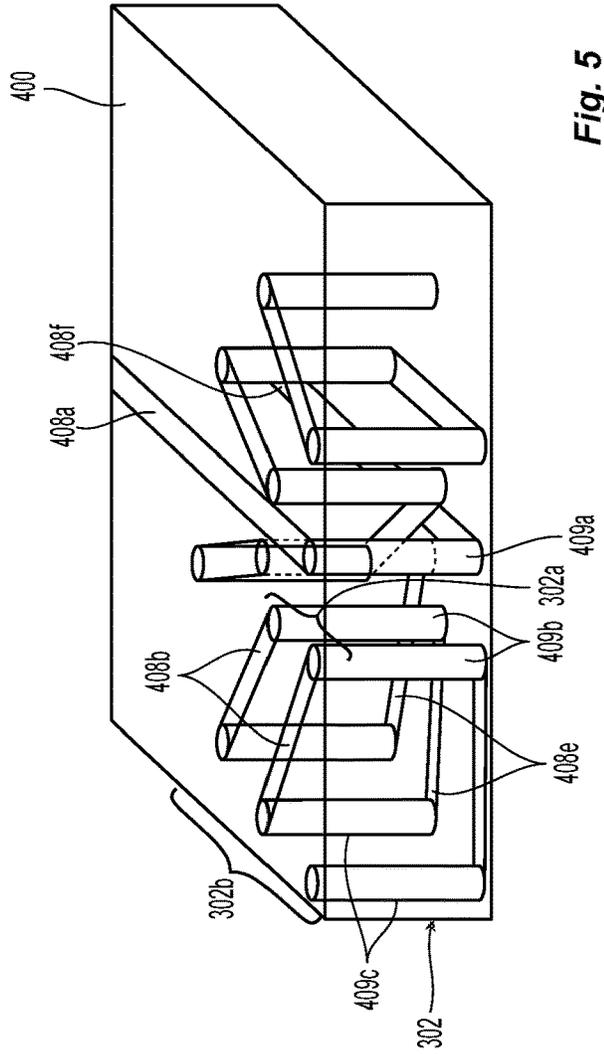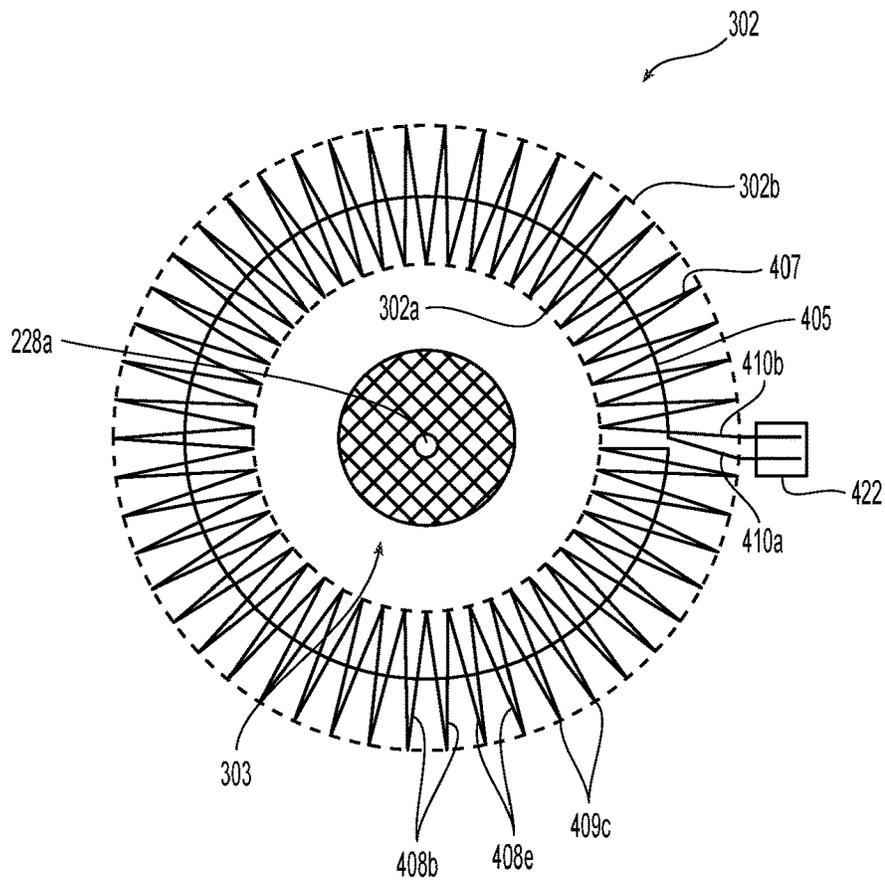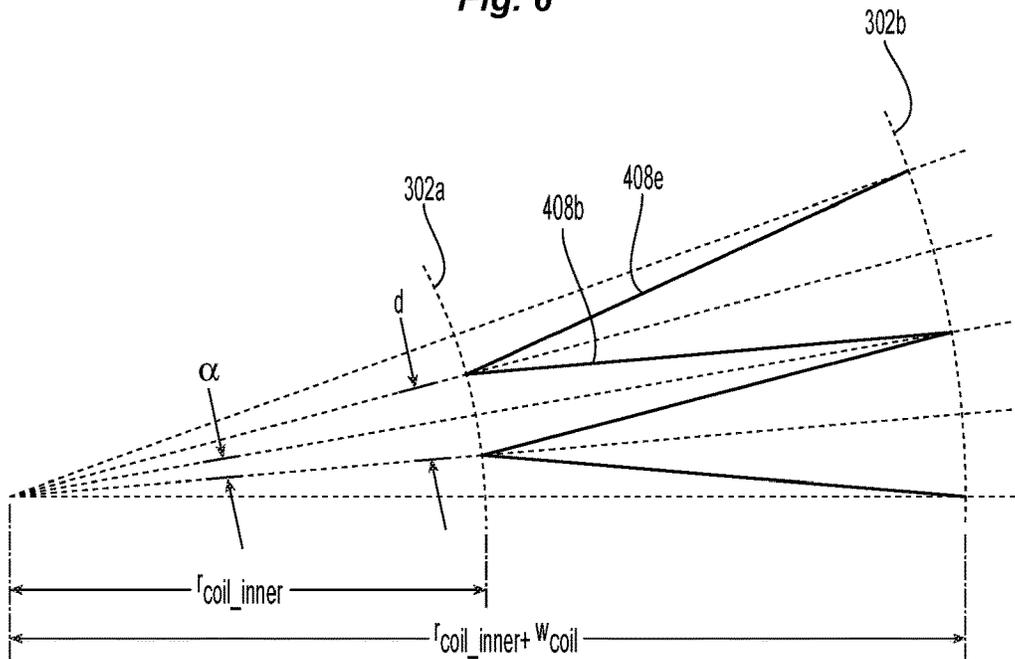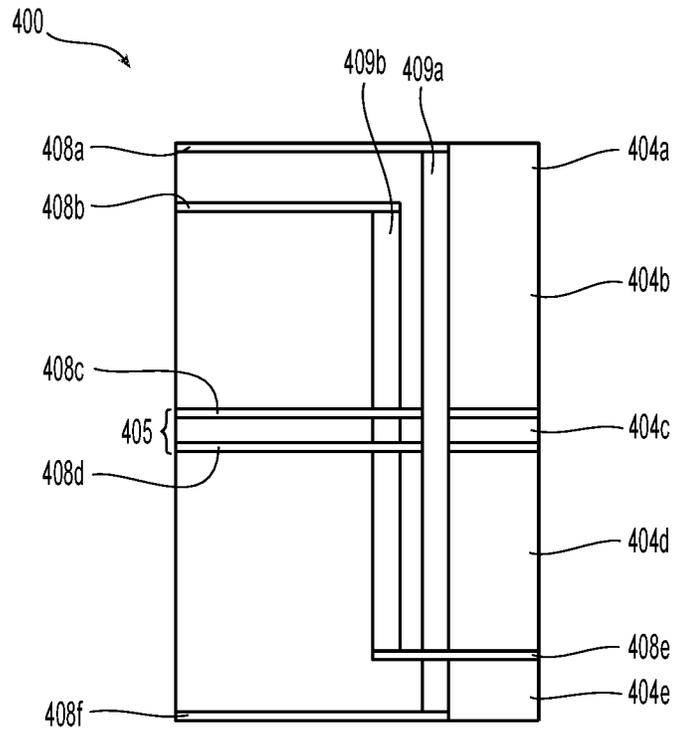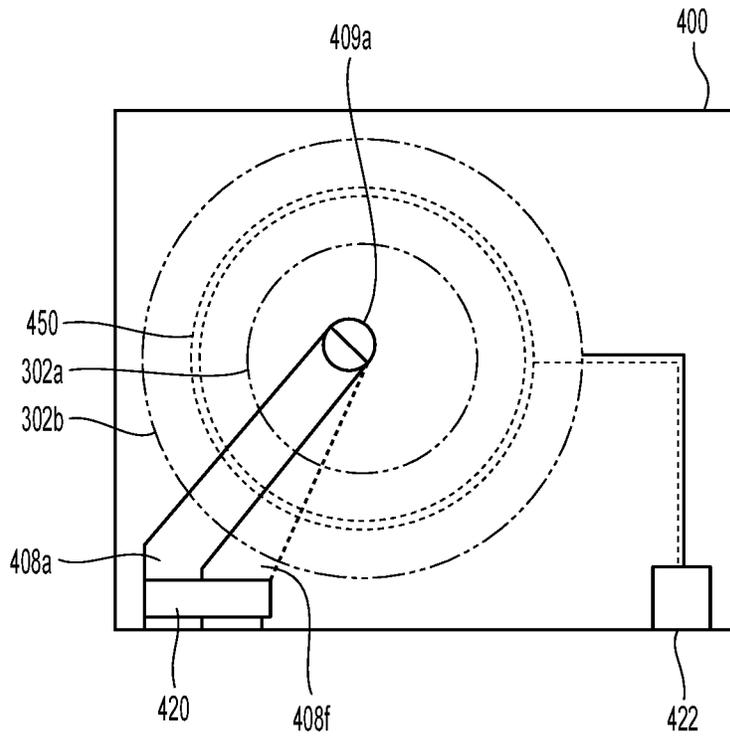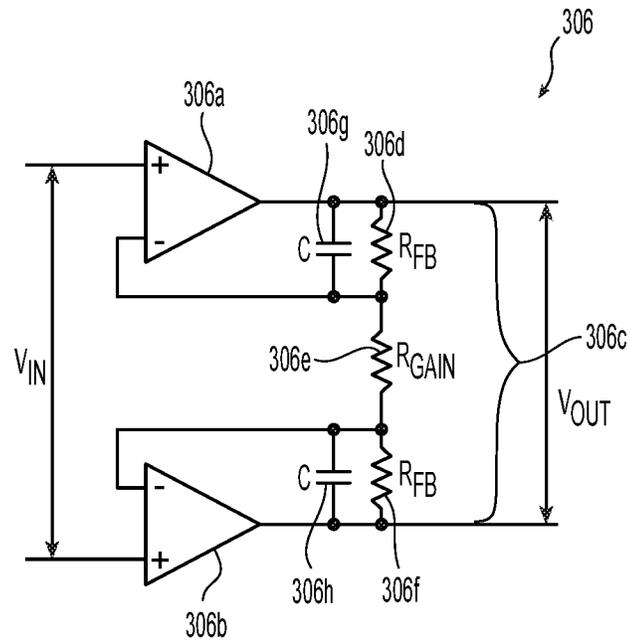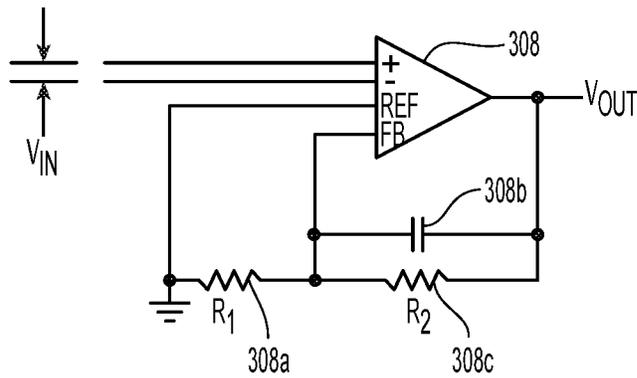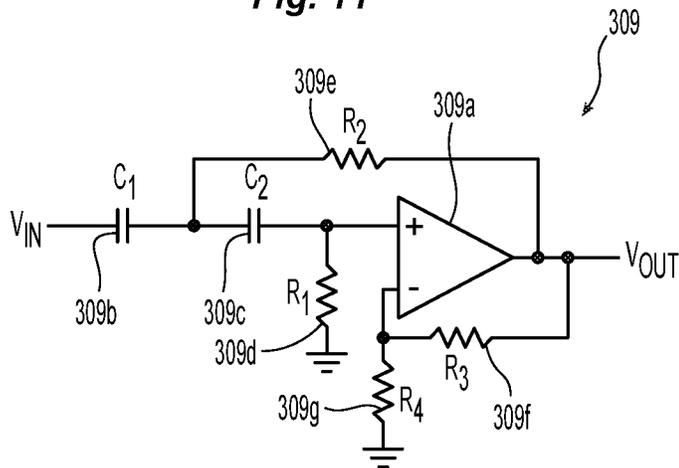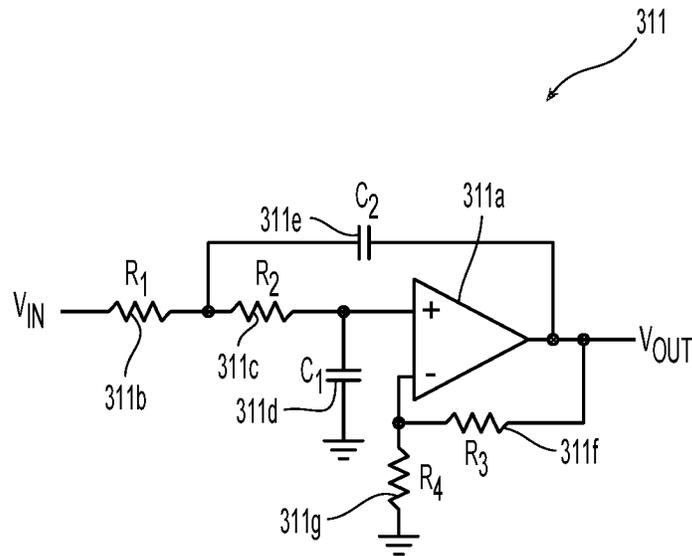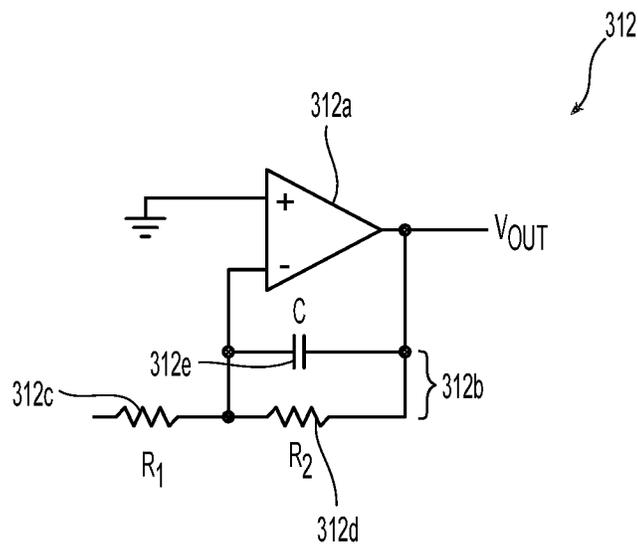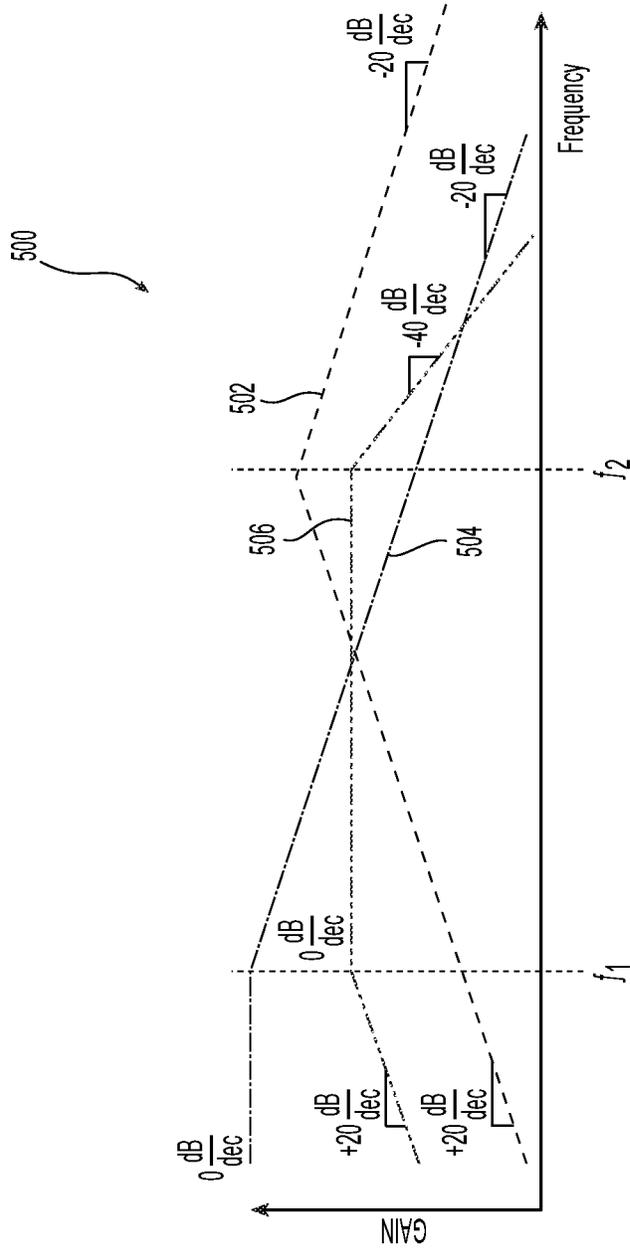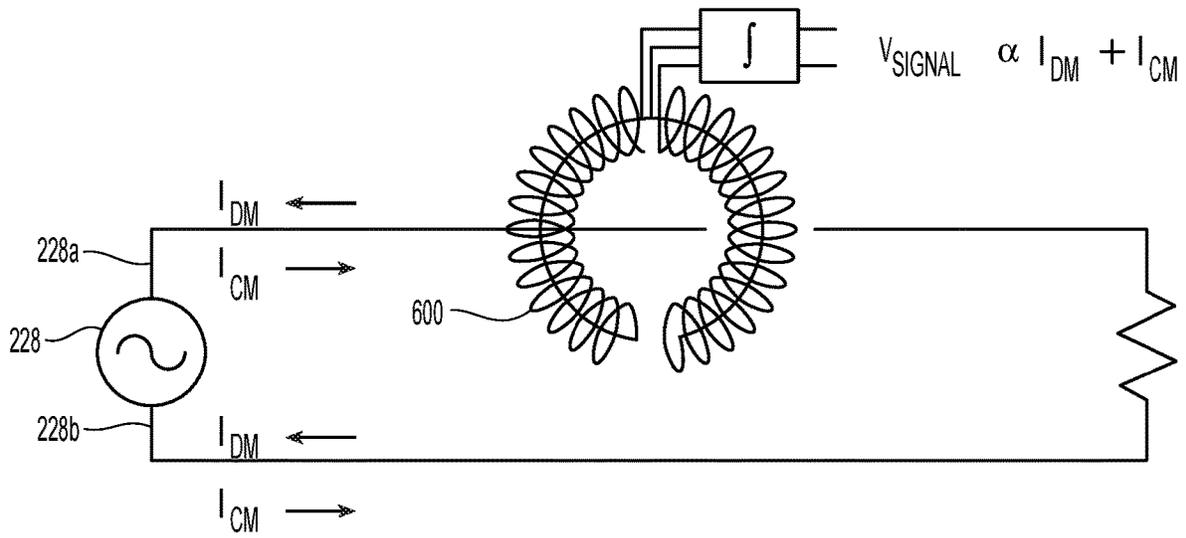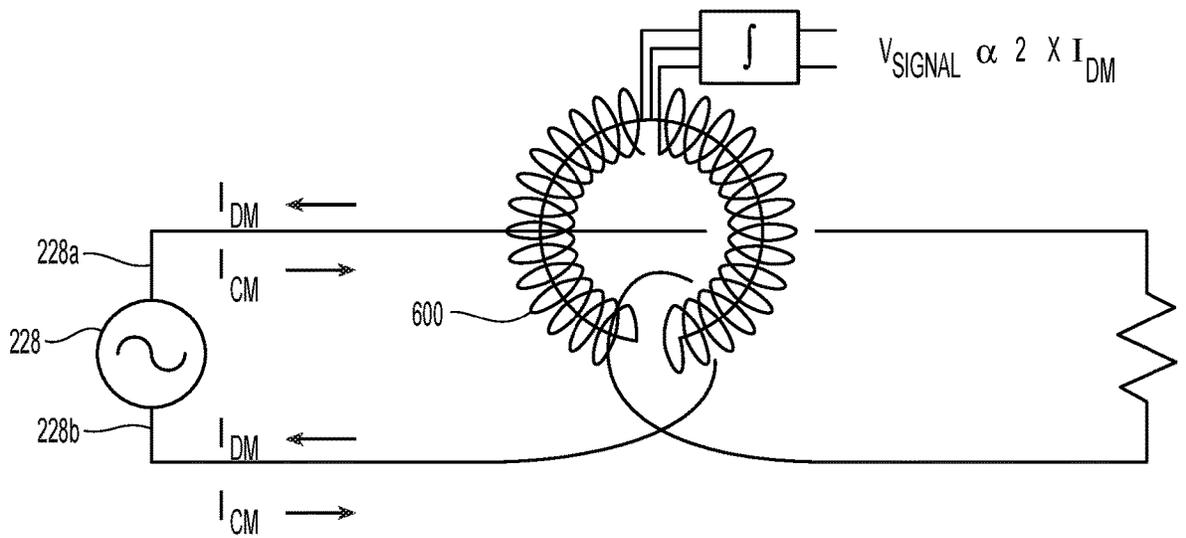
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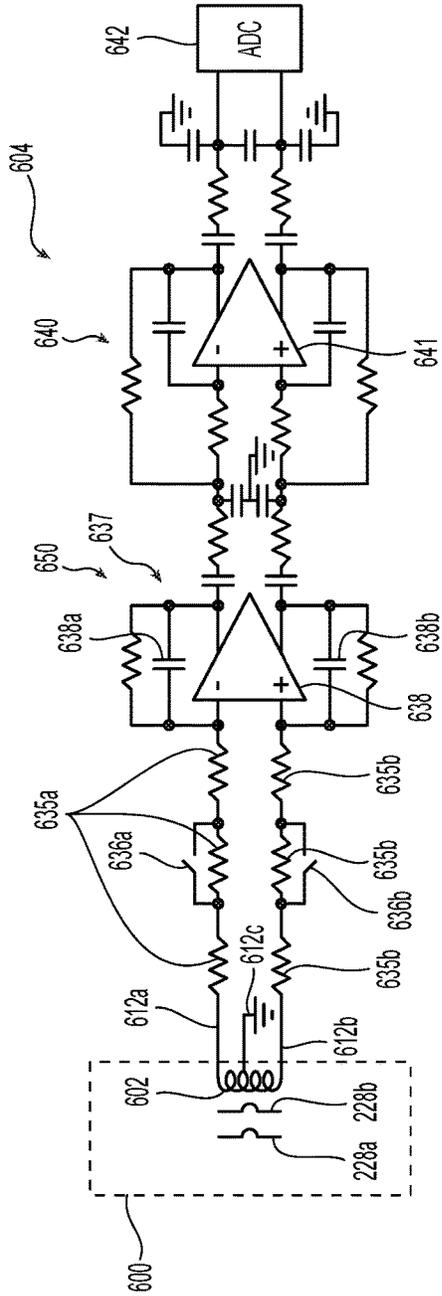
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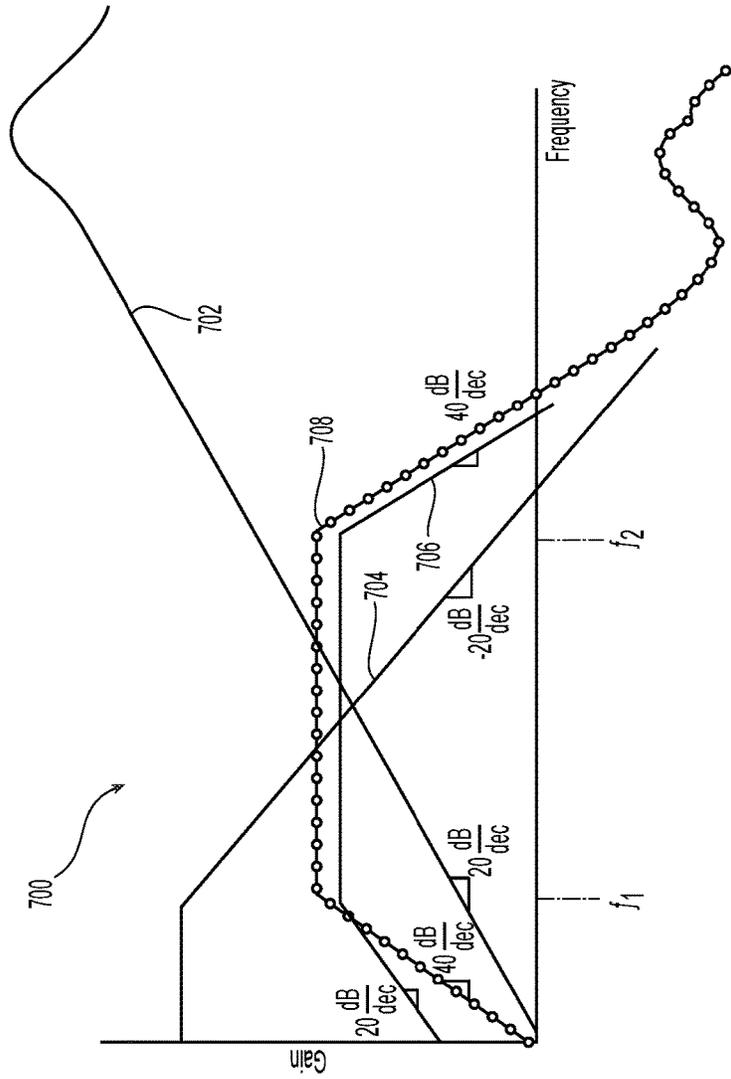
Fig. 20

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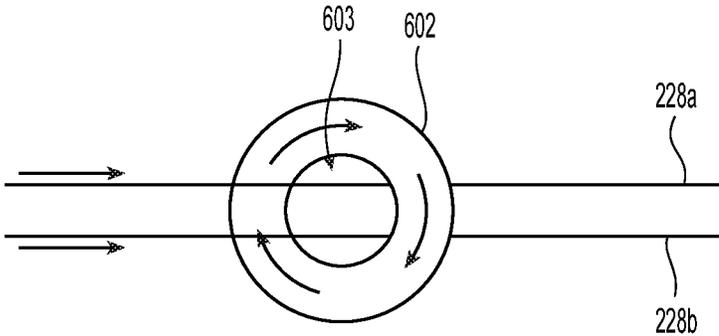
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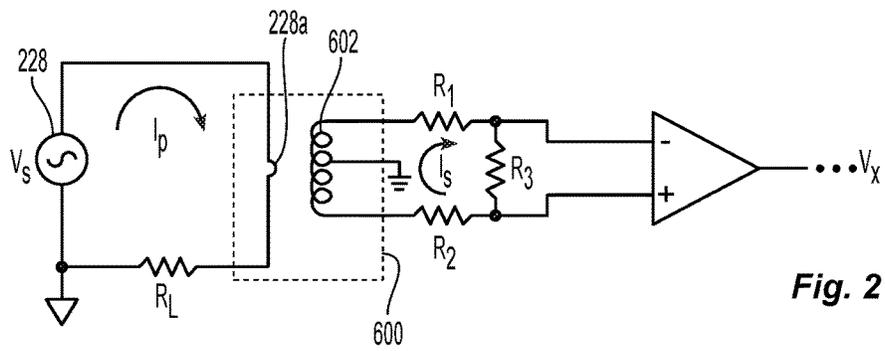
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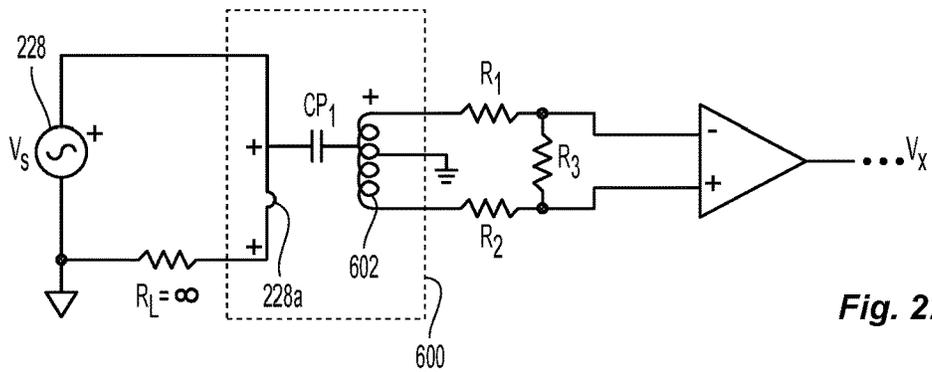
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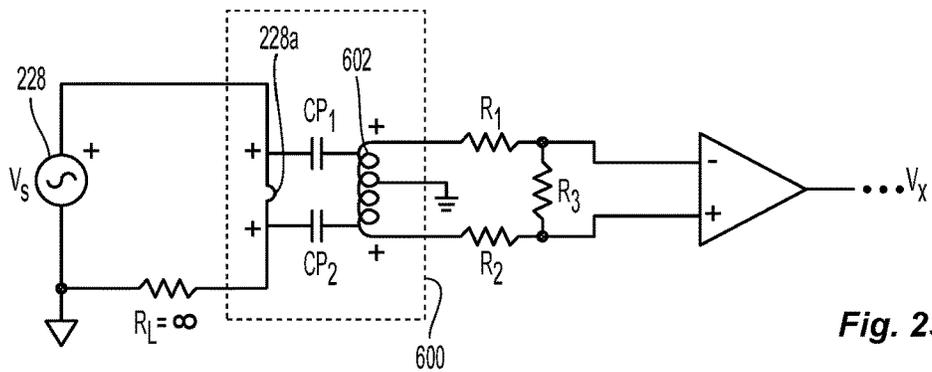
Fig. 23
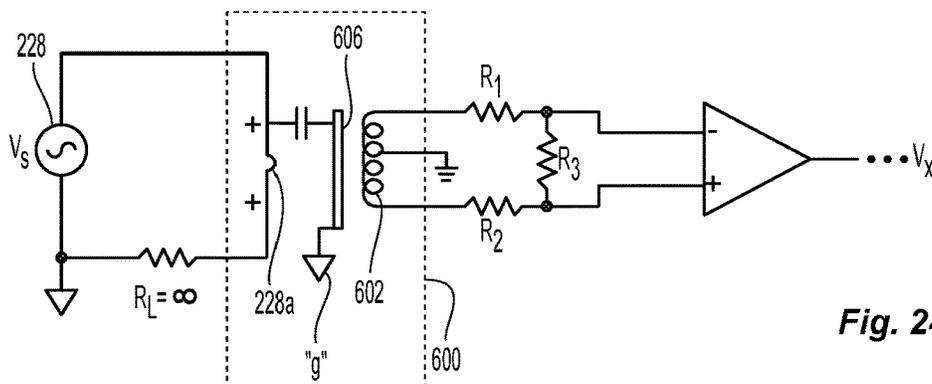
Fig. 24
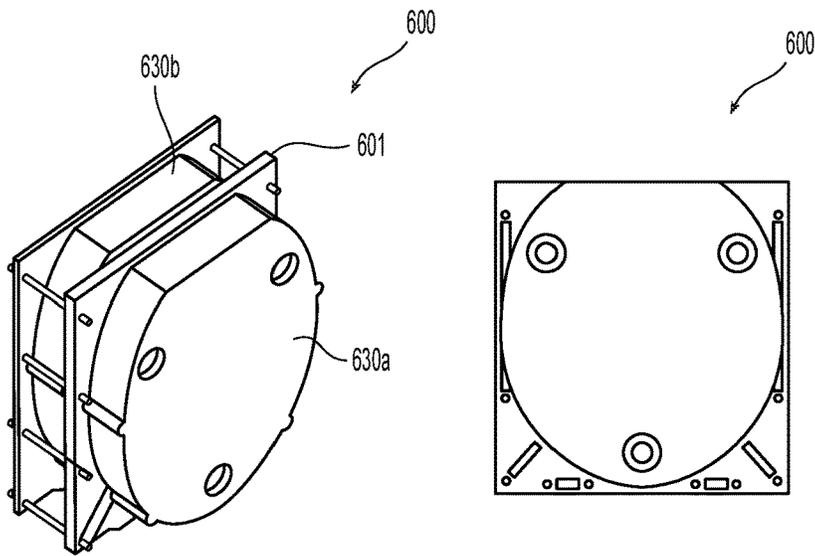
Fig. 25A

Fig. 25B
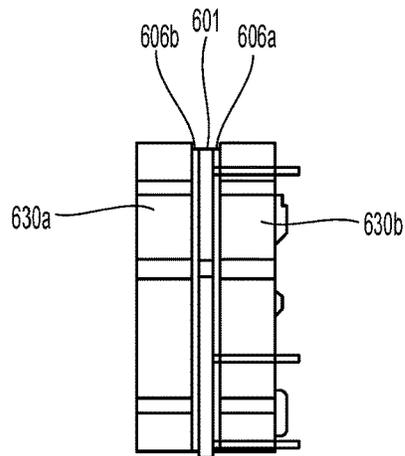
Fig. 25C
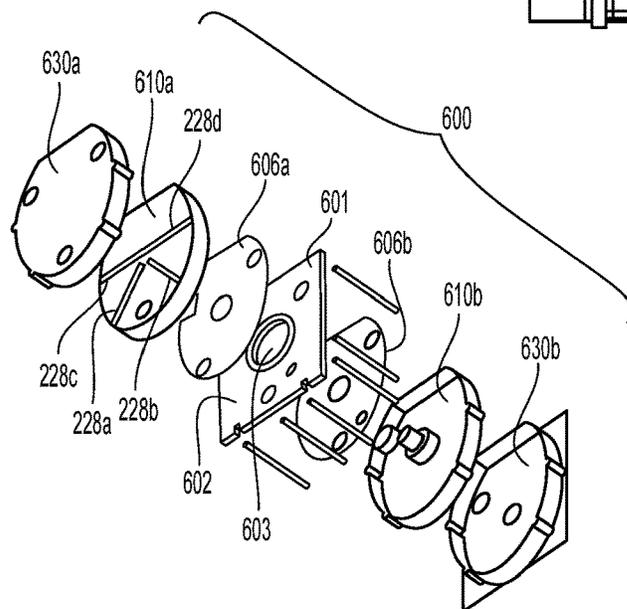
Fig. 25D

Fig. 25E

Fig. 26A

Fig. 26B   *Fig. 26C*
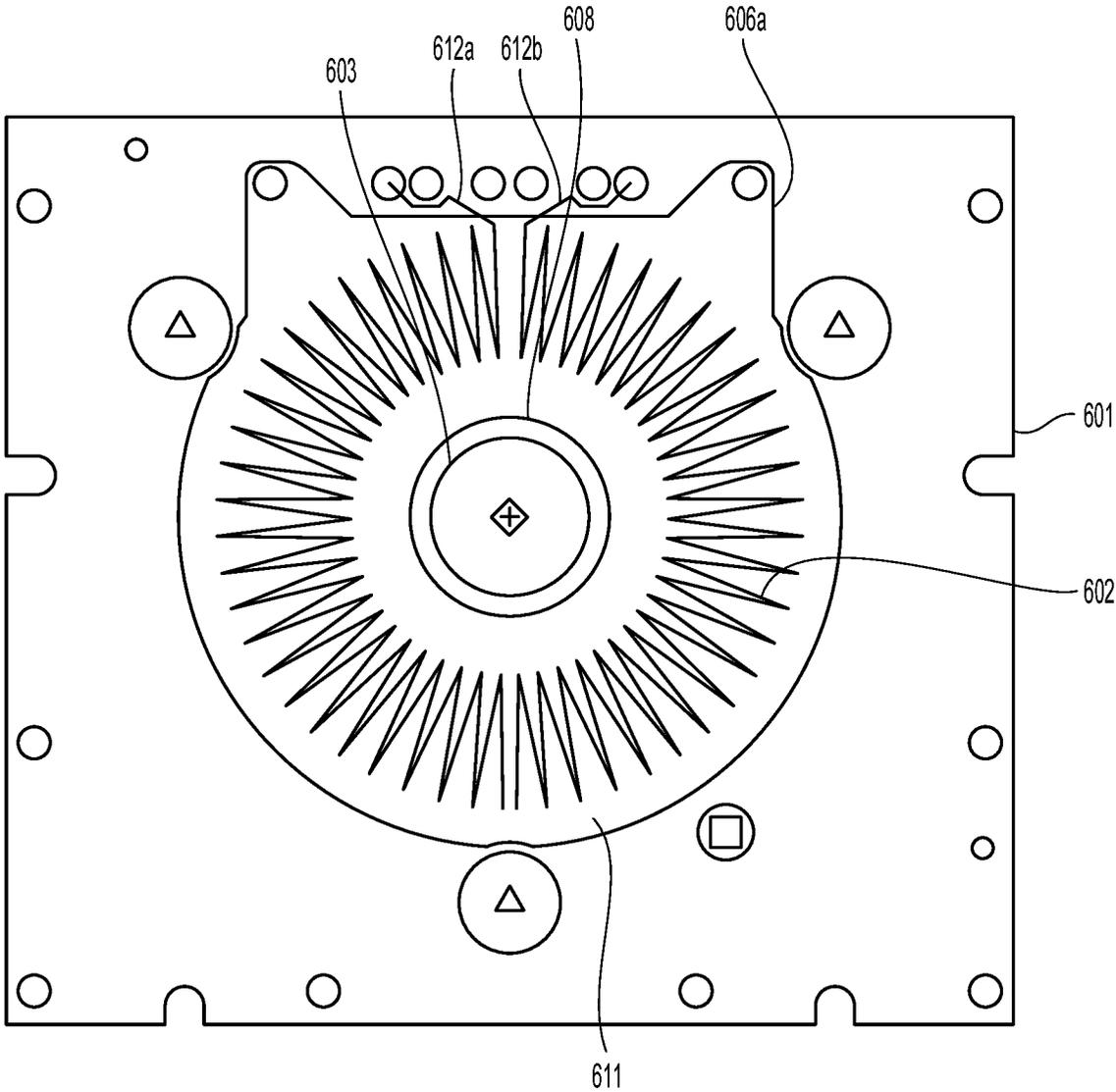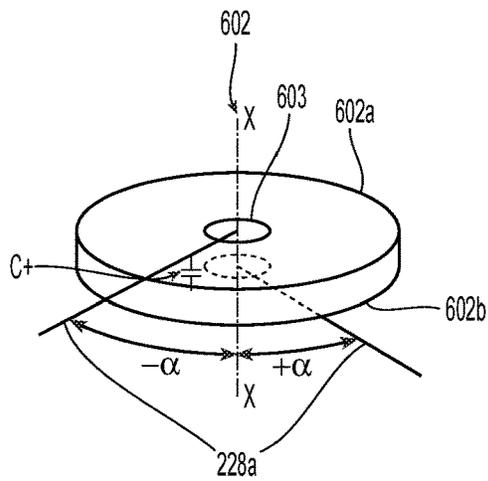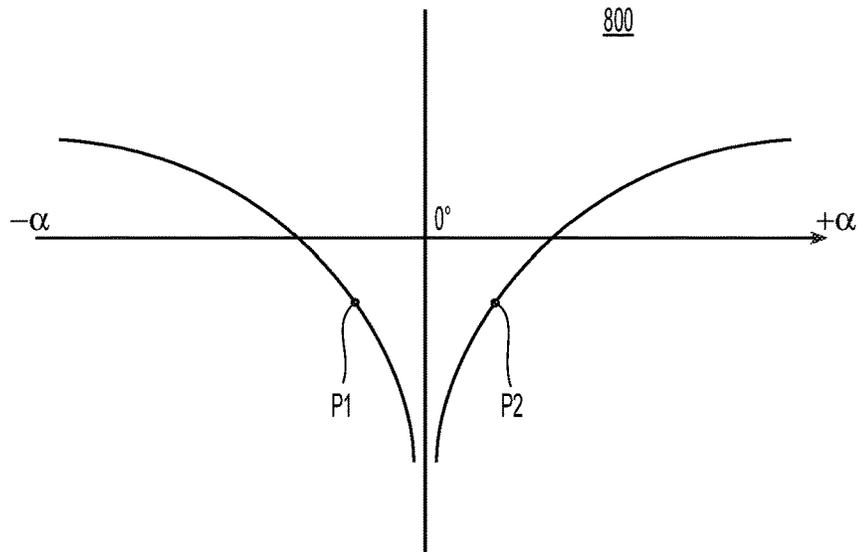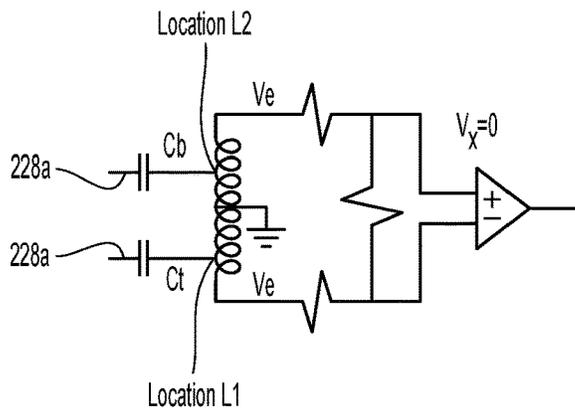
Fig. 26D

Fig. 26E

Fig. 26F
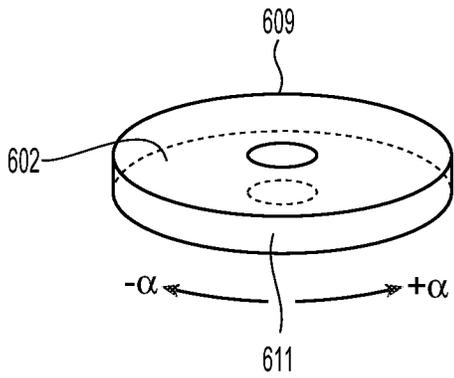
Fig. 27A
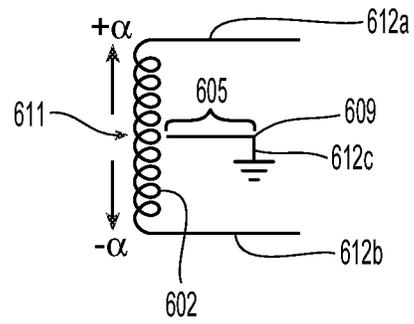
Fig. 27B
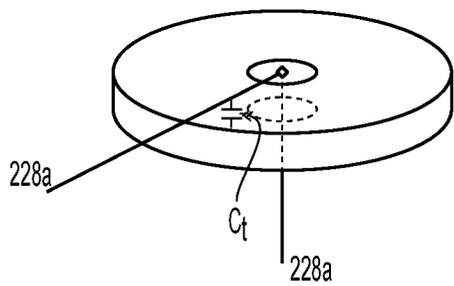
Fig. 28A
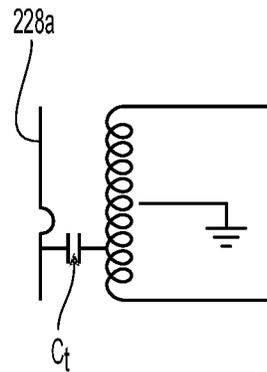
Fig. 28B
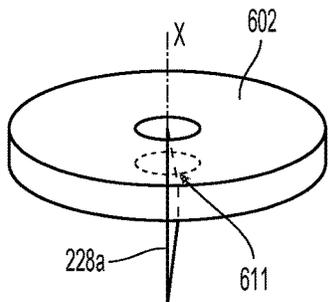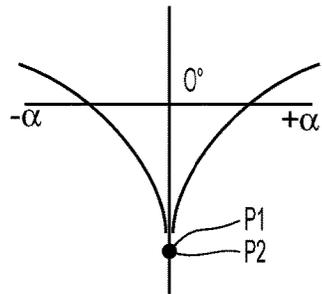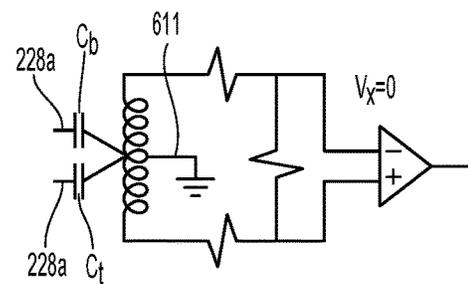
Fig. 29A   *Fig. 29B*   *Fig. 29C*
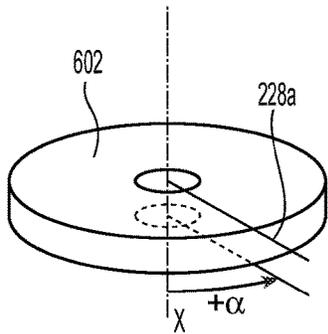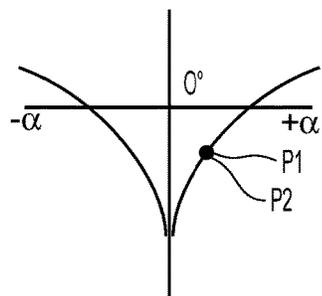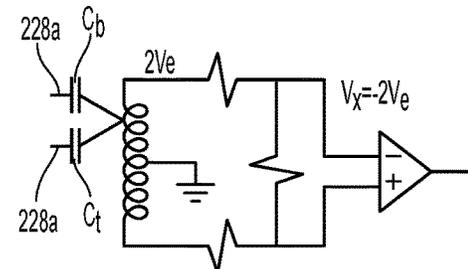
Fig. 30A   *Fig. 30B*   *Fig. 30C*
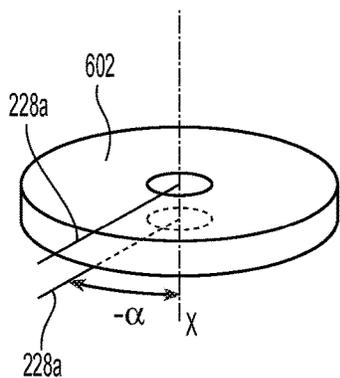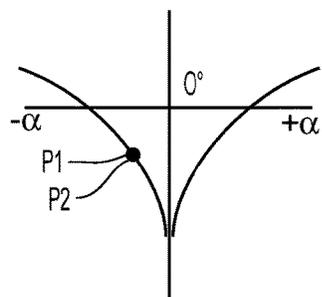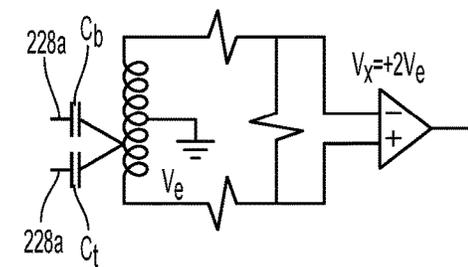
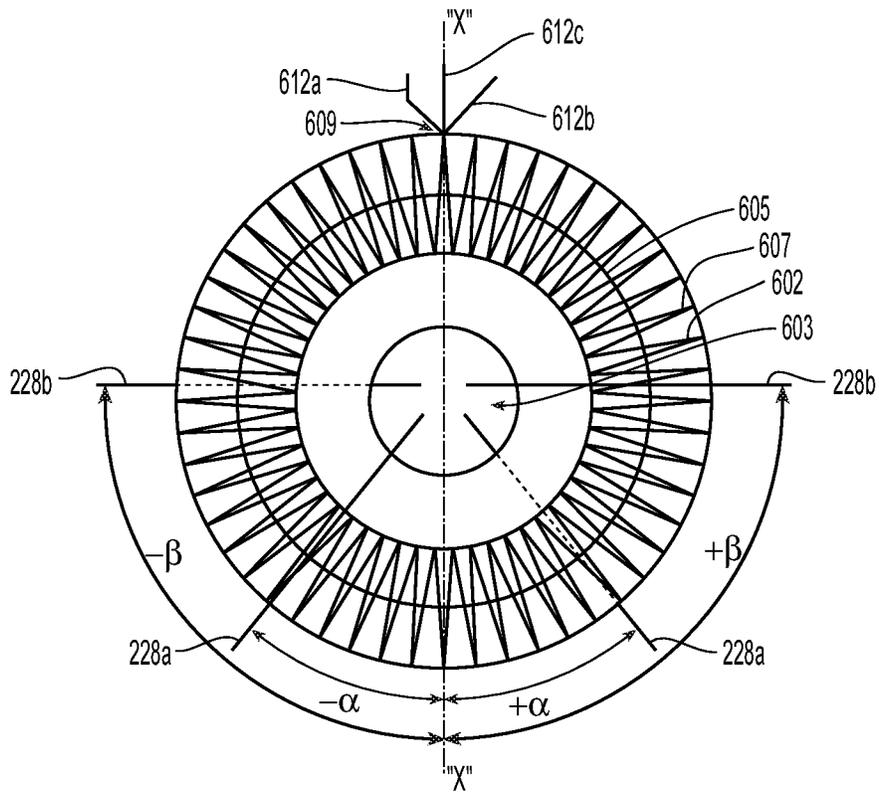*Fig. 31A*   *Fig. 31B*   *Fig. 31C*

Fig. 32A

Fig. 32B

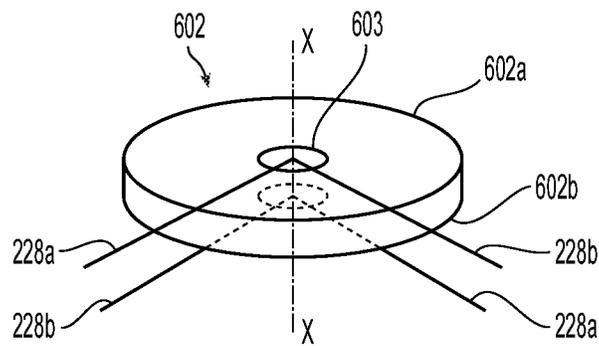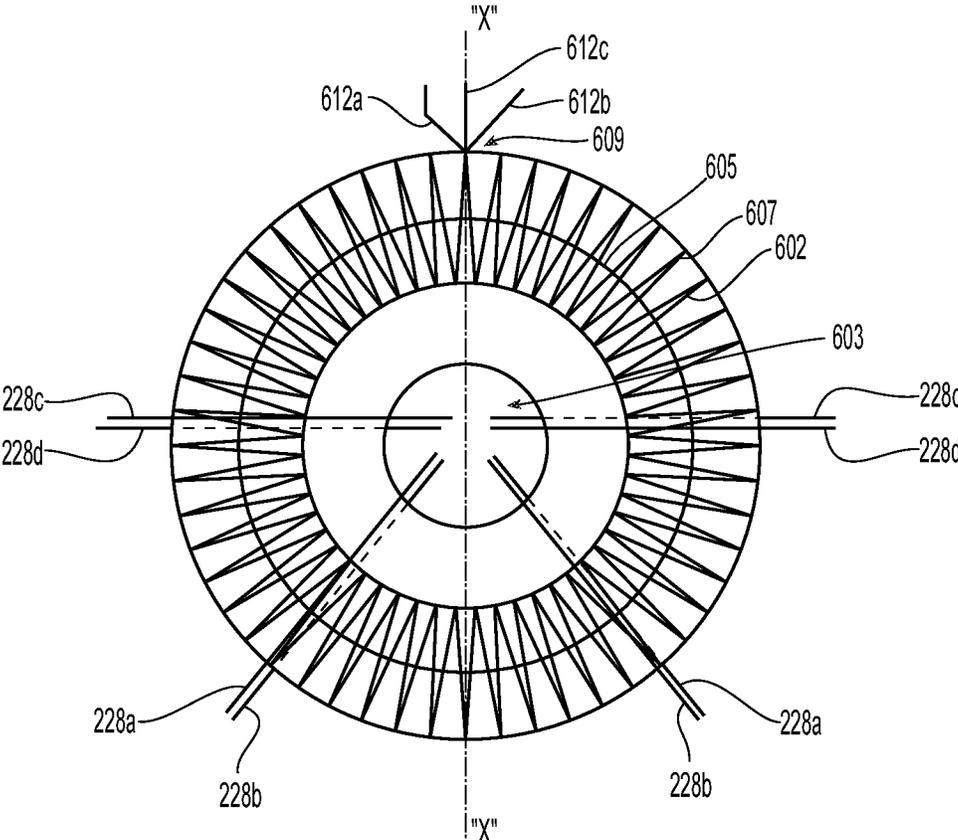*Fig. 33*

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ELECTROSURGICAL GENERATORS AND SENSORS

CROSS-REFERENCE TO RELATED APPLICATION

The present application is a continuation of U.S. patent application Ser. No. 14/557,533, filed on Dec. 2, 2014, which is related to U.S. patent application Ser. No. 14/557,557 filed on Dec. 2, 2014 and U.S. patent application Ser. No. 14/557,579, filed on Dec. 2, 2014. The entire contents of all of the foregoing applications are incorporated by reference herein.

BACKGROUND

Technical Field

The present disclosure relates to an electrosurgical system and method for operating an electrosurgical generator. More particularly, the present disclosure relates to a system, apparatus, and method for measuring current in an electrosurgical generator.

Background of Related Art

Electrosurgery involves application of high radio frequency electrical current to a surgical site to cut, ablate, or coagulate tissue. In monopolar electrosurgery, a source or active electrode delivers radio frequency alternating current from the electrosurgical generator to the targeted tissue. A patient return electrode is placed remotely from the active electrode to conduct the current back to the generator.

In bipolar electrosurgery, return and active electrodes are placed in close proximity to each other such that an electrical circuit is formed between the two electrodes (e.g., in the case of an electrosurgical forceps). In this manner, the applied electrical current is limited to the body tissue positioned between the electrodes. Accordingly, bipolar electrosurgery generally involves the use of instruments where it is desired to achieve a focused delivery of electrosurgical energy between two electrodes positioned on the instrument, e.g. forceps or the like. Electrosurgical procedures outlined above may utilize various tissue and energy parameters in a feedback-based control system. There is continual need to improve sensors that measure various tissue and energy properties utilized in the feedback-based control systems.

SUMMARY

Various embodiments of the present disclosure are described herein with reference to the drawings wherein:

According to one embodiment of the present disclosure, an electrosurgical generator is provided. The generator includes a radio frequency output stage, a sensor for sensing current, and an active lead. The radio frequency output stage is configured to output at least one radio frequency waveform. The sensor includes a current sensor coil including an outer coil including an opening therethrough and an inner coil coupled to and disposed within the outer coil. The active lead is coupled to the radio frequency output stage and passes through the current sensor coil opening. The current sensor coil is configured to output a first signal indicative of a current within the active lead.

In embodiments, the electrosurgical generator may further include at least one return lead coupled to the radio frequency output stage. The at least one return lead may pass

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through the current sensor coil. The current sensor coil may be configured to output a second signal indicative of a current within the at least one return lead. The sensor may further include a conditioning circuit configured to integrate, amplify, and/or filter the first signal or the second signal to output a processed signal indicative of the current of the first signal and/or the second signal. The conditioning circuit may be fully-differential.

In embodiments, the current sensor coil may be disposed within a printed circuit board. In embodiments, the sensor may further include at least one shielding member disposed over the outer coil. The printed circuit board may include a plurality of outer conductive traces. Each trace may be coupled to the at least one active lead and be interconnected by at least one via through the printed circuit board. The printed circuit board may further include a top dielectric layer, a first dielectric intermediate layer, a bottom dielectric layer, and a second dielectric intermediate layer. The outer coil may include a plurality of top conductive traces disposed between the top dielectric layer and the first dielectric intermediate layer of the printed circuit board. A plurality of bottom conductive traces may be disposed between the bottom dielectric layer and the second dielectric intermediate layer of the printed circuit board. The outer conductive traces may be disposed over the outer surfaces of the bottom and top dielectric layers. A plurality of inner and outer vias may interconnect the pluralities of top and bottom conductive traces. The shielding member may be disposed over an outer dielectric layer, which is disposed over the outer surface of at least one of the top dielectric layer or the bottom dielectric layer. The inner coil may include at least one conductive trace disposed within the outer coil and between the first and second dielectric intermediate layers of the printed circuit board.

In embodiments, the current sensor coil may include diametrically opposed first and second ends. Each of the outer coil and the inner coil may include first and second portions separated at the second end. The conditioning circuit may include first and second terminals coupled to the first and second portions of the outer coil, respectively. The first and second portions of the inner coil may be coupled to a third terminal at the first end. The first portions of the outer coil and the inner coil may be coupled to each other at the second end and the second portions of the outer coil and the inner coil may be coupled to each other at the second end. The at least one active lead and/or the at least one return lead may be symmetrically disposed over the current sensor coil about an axis defined between the first and second ends. The at least one active lead and/or the at least one return lead may be disposed at a non-zero angle relative to the axis. The at least one active lead and/or the at least one return lead may be disposed transversely relative to the axis.

In another aspect of the present disclosure, another embodiment of an electrosurgical generator is provided. The electrosurgical generator includes a radio frequency output stage, a sensor for sensing current, and at least one active lead. The radio frequency output stage is configured to output at least one radio frequency waveform. The sensor includes a current sensor coil defining an opening therethrough and diametrically opposed first and second ends. The current sensor coil includes an outer coil including a first semi-circular portion and a second semi-circular portion and an inner coil disposed within the outer coil. The inner coil includes a first semi-circular portion and a second semi-circular portion. The first semi-circular portions and the second semi-circular portions of the inner and outer coils are separated at the second end. The least one active lead

and/or at least one return lead are coupled to the radio frequency output stage and pass through the current sensor coil. The current sensor coil is configured to output a differential signal indicative of a current within the at least one active lead and/or at least one return lead.

In embodiments, the current sensor coil may further include at least one shielding member disposed over the outer coil and define a second opening therethrough in alignment with the opening of the current sensor coil.

In embodiments, the sensor may further include a conditioning circuit coupled to the inner and outer coils at the first end and configured to integrate, amplify, and/or filter the differential signal to output a processed signal indicative of the current.

In embodiments, the at least one active lead and/or the at least one return lead may be symmetrically disposed over the current sensor coil about an axis defined between the first and second ends. In another aspect of the present disclosure, the at least one active lead and/or the at least one return lead may be disposed at a non-zero angle relative to the axis. In yet another aspect of the present disclosure, the at least one active lead and/or the at least one return lead may be disposed transversely relative to the axis.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments of the present disclosure are described herein with reference to the drawings wherein:

FIG. 1 is a perspective view of the components of one illustrative embodiment of an electrosurgical system according to the present disclosure;

FIG. 2 is a front view of one embodiment of an electrosurgical generator according to the present disclosure;

FIG. 3 is a schematic, block diagram of the embodiment of an electrosurgical generator of FIG. 2 according to the present disclosure;

FIG. 4 is a schematic diagram of a current sensor according to the present disclosure;

FIG. 5 is a partially-exposed, isometric view of a current sensor disposed within a printed circuit board according to the present disclosure;

FIG. 6 is a partially-exposed, plan view of a current sensor coil of FIG. 5 according to the present disclosure;

FIG. 7 is an enlarged schematic view of the current sensor coil of FIG. 6 according to the present disclosure;

FIG. 8 is a side, partial cross-sectional view of the printed circuit board of FIG. 5 according to the present disclosure;

FIG. 9 is a plan view of the printed circuit board of FIG. 5 according to the present disclosure;

FIG. 10 is a schematic circuit diagram of a gain amplifier according to the present disclosure;

FIG. 11 is a schematic circuit diagram of a differential to single-ended amplifier according to the present disclosure;

FIG. 12 is a schematic circuit diagram of a high-pass filter according to the present disclosure;

FIG. 13 is a schematic circuit diagram of a low-pass filter according to the present disclosure;

FIG. 14 is a schematic circuit diagram of an integrator according to the present disclosure;

FIG. 15 is a plot of individual and combined gain response of the current sensor coil of FIG. 4 and the integrator shown in FIG. 14 according to the present disclosure;

FIG. 16 is a schematic diagram of the current sensor coil of FIG. 4 according to the present disclosure;

FIG. 17 is a schematic diagram of a differential-mode current sensor coil according to the present disclosure;

FIG. 18 shows another embodiment of a current sensor and conditioning circuit according to the present disclosure;

FIG. 19 is a schematic diagram of the differential-mode current sensor coil of FIG. 17 according to the present disclosure.

FIG. 20 is a plot of individual and combined gain response of a current sensor coil, an integrator, a bandpass filter shown in FIG. 18 according to the present disclosure;

FIG. 21 is a schematic diagram of the current sensor of FIG. 18 according to the present disclosure;

FIG. 22 is a schematic diagram of the current sensor of FIG. 18 with parasitic capacitive coupling according to the present disclosure;

FIG. 23 is a schematic diagram of the current sensor of FIG. 18 with balanced out parasitic capacitive coupling according to the present disclosure;

FIG. 24 is a schematic diagram of the current sensor of FIG. 18 having a shielding member according to the present disclosure;

FIG. 25A is a perspective view of a current sensor coil according to the present disclosure;

FIG. 25B is a front view of the current sensor coil of FIG. 25A according to the present disclosure;

FIG. 25C is a side view of the current sensor coil of FIG. 25A according to the present disclosure;

FIG. 25D is an exploded view of the current sensor coil of FIG. 25A according to the present disclosure;

FIG. 25E is a plan view of the current sensor coil of FIG. 25A according to the present disclosure;

FIG. 26A is a partially-exposed, plan view of a current sensor coil of the current sensor of FIG. 25A according to one embodiment of the present disclosure;

FIG. 26B is an enlarged area 26B of the current sensor coil of FIG. 26A according to the present disclosure;

FIG. 26C is an enlarged area 26C of the current sensor coil of FIG. 26A according to the present disclosure;

FIG. 26D is a perspective, schematic view of the current sensor coil of FIG. 26A according to the present disclosure;

FIG. 26E is a plot of an erroneous error signal as function of wire position of the current sensor coil of FIG. 26A as a function of an angle of leads passing therethrough according to the present disclosure;

FIG. 26F is a schematic diagram of the current sensor coil of FIG. 26A with parasitic capacitive coupling according to the present disclosure;

FIG. 27A is a perspective, schematic view of a current sensor coil according to another embodiment of the present disclosure;

FIG. 27B is a schematic diagram of the current sensor of FIG. 27A according to the present disclosure;

FIG. 28A is a perspective, schematic view of the current sensor coil according to another embodiment of the present disclosure;

FIG. 28B is a schematic diagram of the current sensor of FIG. 28A with parasitic capacitive coupling according to the present disclosure;

FIG. 29A is a perspective, schematic view of the current sensor coil according to another embodiment of the present disclosure;

FIG. 29B is a plot of an erroneous error signal as function of lead position of the current sensor coil of FIG. 29A as a function of an angle of leads passing therethrough according to the present disclosure;

FIG. 29C is a schematic diagram of the current sensor of FIG. 29A with parasitic capacitive coupling according to the present disclosure;

FIG. **30A** is a perspective, schematic view of the current sensor coil according to another embodiment of the present disclosure;

FIG. **30B** is a plot of an erroneous error signal as function of lead position of the current sensor coil of FIG. **30A** as a function of an angle of leads passing therethrough according to the present disclosure;

FIG. **30C** is a schematic diagram of the current sensor of FIG. **30A** with parasitic capacitive coupling according to the present disclosure;

FIG. **31A** is a perspective, schematic view of the current sensor coil according to another embodiment of the present disclosure;

FIG. **31B** is a plot of an erroneous error signal as function of lead position of the current sensor coil of FIG. **31A** as a function of an angle of leads passing therethrough according to the present disclosure;

FIG. **31C** is a schematic diagram of the current sensor of FIG. **31A** with parasitic capacitive coupling according to the present disclosure;

FIG. **32A** is a partially-exposed, plan view of a current sensor coil of the current sensor according to another embodiment of the present disclosure;

FIG. **32B** is a perspective, schematic view of the current sensor of FIG. **32A** according to the present disclosure; and

FIG. **33** is a partially-exposed, plan view of a current sensor coil of the current sensor according to a further embodiment of the present disclosure.

DETAILED DESCRIPTION

Particular embodiments of the present disclosure are described hereinbelow with reference to the accompanying drawings. In the following description, well-known functions or constructions are not described in detail to avoid obscuring the present disclosure in unnecessary detail.

A generator according to the present disclosure can perform monopolar and/or bipolar electrosurgical procedures, including, for example, cutting, coagulation, ablation, and vessel sealing procedures. The generator may include a plurality of outputs for interfacing with various electrosurgical instruments (e.g., a monopolar instrument, return electrode, bipolar electrosurgical forceps, footswitch, etc.). Further, the generator includes electronic circuitry configured to generate radio frequency energy specifically suited for various electrosurgical modes (e.g., cut, blend, coagulate, division with hemostasis, fulgurate, spray, etc.) and procedures (e.g., monopolar, bipolar, vessel sealing). In embodiments, the generator may be embedded, integrated or otherwise coupled to the electrosurgical instruments providing for an all-in-one electrosurgical apparatus. In further embodiments, the generator may include a current sensor coil configured to sense current supplied to one or more electrosurgical instruments. The current sensor coil according to the present disclosure minimizes and/or eliminates, the unwanted signal that is coupled via the parasitic capacitances, which can lead to erroneous current sensor measurements. In embodiments, coupling is directed to ground through a shielding member. In further embodiments, the signal is zeroed by coupling an additional equal, but opposite voltage signal.

FIG. **1** is a perspective view of the components of one illustrative embodiment of a bipolar and monopolar electrosurgical system **10** according to the present disclosure. The system **10** may include one or more monopolar electrosurgical instruments **20** having one or more active electrodes **23** (e.g., electrosurgical cutting probe, ablation electrode(s),

etc.) for treating tissue of a patient. Electrosurgical alternating current is supplied to the instrument **20** by a generator **200** via a supply line **24** that is connected to an active terminal **230** (FIG. **3**) of the generator **200**, allowing the instrument **20** to cut, coagulate, ablate and/or otherwise treat tissue. The alternating current is returned to the generator **200** through a return electrode pad **26** via a return line **28** at a return terminal **232** (FIG. **3**) of the generator **200**. For monopolar operation, the system **10** may include a plurality of return electrode pads **26** that, in use, are disposed on a patient to minimize the chances of tissue damage by maximizing the overall contact area with the patient. In addition, the generator **200** and the return electrode pads **26** may be configured for monitoring tissue-to-patient contact to ensure that sufficient contact exists therebetween.

The system **10** may also include one or more bipolar electrosurgical instruments, for example, a bipolar electrosurgical forceps **30** having one or more electrodes for treating tissue of a patient. The electrosurgical forceps **30** includes a housing **31** and opposing jaw members **33** and **35** disposed at a distal end of a shaft **32**. The jaw members **33** and **35** have one or more active electrodes **34** and a return electrode **36** disposed therein, respectively. The active electrode **34** and the return electrode **36** are connected to the generator **200** through cable **38** that includes the supply and return lines **24, 28** coupled to the active and return terminals **230, 232**, respectively (FIG. **3**). The electrosurgical forceps **30** is coupled to the generator **200** at a connector having connections to the active and return terminals **230** and **232** (e.g., pins) via a plug disposed at the end of the cable **38**, wherein the plug includes contacts from the supply and return lines **24, 28** as described in more detail below.

With reference to FIG. **2**, a front face **240** of the generator **200** is shown. The generator **200** may be any suitable type (e.g., electrosurgical, microwave, etc.) and may include a plurality of connectors **250, 252, 254, 256, 258, 260, 262** to accommodate various types of electrosurgical instruments (e.g., electrosurgical forceps **30**, etc.).

The generator **200** includes a user interface **241** having one or more display screens or information panels **242, 244, 246** for providing the user with variety of output information (e.g., intensity settings, treatment complete indicators, etc.). Each of the screens **242, 244, 246** is associated with corresponding connectors **250-262**. The generator **200** includes suitable input controls (e.g., buttons, activators, switches, touch screen, etc.) for controlling the generator **200**. The display screens **242, 244, 246** are also configured as touch screens that display a corresponding menu for the electrosurgical instruments (e.g., electrosurgical forceps **30**, etc.). The user then adjusts inputs by simply touching corresponding menu options.

Screen **242** controls monopolar output and the devices connected to the connectors **250** and **252**. Connector **250** is configured to couple to a monopolar electrosurgical instrument (e.g., electrosurgical instrument **20**) and connector **252** is configured to couple to a foot switch (not shown). The foot switch provides for additional inputs (e.g., replicating inputs of the generator **200**). Connector **254** is configured to couple to electrode pad **26**. Screen **244** controls monopolar and bipolar output and the devices connected to the connectors **256** and **258**. Connector **256** is configured to couple to other monopolar instruments. Connector **258** is configured to couple to a bipolar instrument (not shown).

Screen **246** controls bipolar sealing procedures performed by the forceps **30** that may be plugged into the connectors **260** and **262**. The generator **200** outputs energy through the connectors **260** and **262** suitable for sealing tissue grasped

by the forceps **30**. In particular, screen **246** outputs a user interface that allows the user to input a user-defined intensity setting. The user-defined setting may be any setting that allows the user to adjust one or more energy delivery parameters, such as power, current, voltage, energy, etc. or sealing parameters, such as energy rate limiters, sealing duration, etc. The user-defined setting is transmitted to a controller **224** of generator **200** (FIG. **3**) where the setting may be saved in memory **226**. In embodiments, the intensity setting may be a number scale, such as for example, from one to ten or one to five. In embodiments, the intensity setting may be associated with an output curve of the generator **200**. The intensity settings may be specific for each forceps **30** being utilized, such that various instruments provide the user with a specific intensity scale corresponding to the forceps **30**.

FIG. **3** shows a schematic block diagram of the generator **200** configured to output electrosurgical energy. The generator **200** includes a controller **224**, a power supply **227**, and a radio-frequency (RF) amplifier **228**. The power supply **227** may be a high voltage, DC power supply connected to an AC source (e.g., line voltage) and provides high voltage, DC power to the RF amplifier **228** via leads **227a** and **227b**, which then converts high voltage, DC power into treatment energy (e.g., electrosurgical or microwave) and delivers the energy to the active terminal **230**. The current is returned thereto via the return terminal **232** as energy is dissipated into the tissue. The active and return terminals **230** and **232** are coupled to the RF amplifier **228** through an isolation transformer **229**. The RF amplifier **228** is configured to operate in a plurality of modes, during which the generator **200** outputs corresponding waveforms having specific duty cycles, peak voltages, crest factors, etc. It is envisioned that in other embodiments, the generator **200** may be based on other types of suitable power supply topologies.

The controller **224** includes a processor **225** operably connected to a memory **226**, which may include transitory type memory (e.g., RAM) and/or non-transitory type memory (e.g., flash media, disk media, etc.). The processor **225** includes an output port that is operably connected to the power supply **227** and/or RF amplifier **228** allowing the processor **225** to control the output of the generator **200** according to either open and/or closed control loop schemes. A closed loop control scheme is a feedback control loop, in which a plurality of sensors measure a variety of tissue and energy properties (e.g., tissue impedance, tissue temperature, output power, current and/or voltage, etc.), and provide feedback to the controller **224**. The controller **224** then signals the power supply **227** and/or RF amplifier **228**, which adjusts the DC and/or power supply, respectively. Those skilled in the art will appreciate that the processor **225** may be substituted for by using any logic processor (e.g., control circuit) adapted to perform the calculations and/or set of instructions described herein including, but not limited to, field programmable gate array, digital signal processor, and combinations thereof.

The generator **200** according to the present disclosure includes a plurality of sensors **280**, e.g., an RF current sensor **280a**, and an RF voltage sensor **280b**. Various components of the generator **200**, namely, the RF amplifier **228**, the RF current and voltage sensors **280a** and **280b**, may be disposed on a printed circuit board (PCB). The RF current sensor **280a** is coupled to the plurality of active leads **228a** and/or plurality of return leads **228b** and provides measurements of the RF current supplied by the RF amplifier **228**. The RF voltage sensor **280b** is coupled to the active and return terminals **230** and **232** and provides measurements of the RF

voltage supplied by the RF amplifier **228**. In embodiments, the RF current and voltage sensors **280a** and **280b** may be coupled to active and return leads **228a** and **228b**, which interconnect the active and return terminals **230** and **232** to the RF amplifier **228**, respectively.

The RF current and voltage sensors **280a** and **280b** provide the sensed RF voltage and current signals, respectively, to the controller **224**, which then may adjust output of the power supply **227** and/or the RF amplifier **228** in response to the sensed RF voltage and current signals. The controller **224** also receives input signals from the input controls of the generator **200**, the instrument **20** and/or forceps **30**. The controller **224** utilizes the input signals to adjust the power output by the generator **200** and/or performs other control functions thereon.

Transformers are conventionally used as current and voltage sensors as they provide a required patient isolation. However, the gain that transformers provide fluctuates due to temperature, signal amplitude, etc. This makes accurate readings difficult with respect to the phase and gain-bandwidth of the sensor signals. As a result, the signals need to be post-processed to arrive at accurate representations. The present disclosure provides for novel current sensor **280a** which overcome the problems of conventional sensors.

FIG. **4** shows an RF current sensor **300**, which includes a conditioning circuit **301** and a current sensor coil **302**. As used herein, the term "current sensor coil" refers to an electrical device for measuring alternating current (e.g., RF current) and includes an outer conductor coil (e.g., toroid) that acts as an active conductor wrapped around an inner conductor, a so-called "Bucking coil" that acts as a return conductor and a lead **228a** carrying the current passing through an opening **303** (FIG. **6**) in the coil **302**. The coil **302** may have any suitable shape such as helical, toroidal, etc. In embodiments, the coil may have a polygonal cross-section. The current sensor coil **302** may include a low permeability core (e.g., air core) and provides a voltage output having a time-derivative of the current being measured to a conditioning circuit that integrates the output to provide a voltage signal indicative of the current. In embodiments, the current sensor coil **302** may be implemented on a printed circuit board and may include an opening so that the current sensor coil **302** may be wrapped about the conductor carrying the current to be measured. In further embodiments, the current sensor coil **302** may also be implemented using wire and may be wound around a toroidal magnetic core.

The current sensor coil **302** is coupled to conditioning circuit **301** having a resistor network **304**, which includes resistors **304a** and **304b**. In embodiments, the conditioning circuit **301** may be implemented as any integrator (e.g., logic processor) or differential amplifier. The resistor network **304** removes resonance of the coil **302** at its resonant frequency. As described in further details below with respect to FIGS. **5-9**, the current sensor coil **302** is disposed about one or more active leads **228a** and the coil **302** is configured to measure the current passing therethrough as a sensor signal. The sensor signal from the coil **302** is then supplied to an optional gain amplifier **306** which increases the amplitude of the sensor signal and buffers the coil **302**. The gain amplifier **306** or the coil **302**, if the gain amplifier **306** is not used, is also coupled to an amplifier **308**, which is in turn, coupled to a bandpass filter **310**. The amplifier **308** is a differential-to-single-ended converter whose function is to convert the differential signal from the coil **302** to a single-ended signal. The amplifier **308** may have a monolithic configuration that provides improved common mode rejection.

The bandpass filter 310 removes higher and lower frequency components of the sensor signal which is then transmitted to an integrator 312. Since the voltage that is induced in the current sensor coil 302 is proportional to the rate of change of current that is flowing through the active lead 228a, the integrator 312 is utilized to provide an output sensor signal that is proportional to the current.

In embodiments, the integrator 312 may be coupled to a switchable attenuation circuit 314, which may include one or more actively switched components. The attenuation circuit 314 may then be coupled to additional components such as an offset circuit 316, analog-digital converters, and the like prior to supplying the signal to the controller 224.

FIGS. 5-9 show the current sensor coil 302 according to the present disclosure. The coil 302 has a substantially circular shape having an opening 303 (FIG. 6) defined therethrough. The active lead 228a is disposed through the opening 303 of the coil 302, allowing the coil 302 to measure the current flow through the active lead 228a. If the return lead 228b is also being measured, additional traces may be used to provide for passage through the opening 303 of the current sensor coil 302 as described in detail below with respect to FIGS. 17-33.

As shown in FIGS. 5 and 6, the coil 302 has a substantially toroidal shape and is formed on a printed circuit board (PCB) 400 and includes an inner circumferential region 302a and an outer circumferential region 302b. The coil 302 includes forming an inner portion ("Bucking coil") 405 of the coil 302 and an outer coil 407. In embodiments, the coil 302 may have any other suitable shape (e.g., having a polygonal cross-section) with the outer coil 407 wrapped about the inner coil 405 and defining an opening through the coil 302. In embodiments, the coil 302 may be a coil-wrapped phenolic toroid having a low permeability (p).

In embodiments, where only one of the active leads 228a is used, the magnetic field is reflective of the current Ip passing only through the active lead 228a. The outer coil 407 detects the magnetic field in either embodiment and produces a first voltage corresponding to the first magnetic field. The outer coil 407 also may detect a second unwanted magnetic field and produces a second voltage corresponding to the second magnetic field. The second magnetic field is orthogonal to the first magnetic field and is not related to the sensed current. The inner coil 405 senses the second magnetic field and produces a third voltage proportional to the second magnetic field. The second voltage and third voltage produced have approximately the same magnitude such that they cancel each other. In embodiments where the plurality of active leads 228a and/or plurality of return leads 228b are disposed together, the current flowing through the active leads 228a and return leads 228b produce a net first magnetic field proportional to the sensed current Is.

The PCB 400 may be a multilayer PCB formed from any suitable dielectric material, including, but not limited to composite materials composed of woven fiberglass cloth with an epoxy resin binder such as FR-4 grade as designated by National Electrical Manufacturers Association. As shown in FIG. 8, the PCB 400 includes a first or top layer 404a and a bottom layer 404e. For simplicity FIG. 5, FIG. 6, FIG. 8, and FIG. 9 will show only the active lead 230. It will be understood that in every case a plurality of active leads and/or a plurality of return leads may be used. The active lead 228a is coupled to conductive traces 408a and 408f, respectively, which are disposed over the top and bottom layers 404a and 404e as shown in FIGS. 8 and 9. The active lead 228a may be coupled to a patient side connector 420 disposed on the PCB 400 as shown in FIG. 9. The traces

408a and 408f are interconnected through the opening 303 (FIG. 6) using one or more vias 409a, which pass through the entire PCB 400 (e.g., layers 404a-404e).

The outer coil 407 includes a top trace 408b disposed between the top layer 404a and an intermediate layer 404b of the PCB 400. The outer coil 407 also includes a bottom trace 408e disposed between the bottom layer 404e and an intermediate layer 404d of the PCB 400. The traces 408b and 408e are interconnected by a plurality of inner vias 409b and outer vias 409c. The layers 404a and 404e insulate the coil 302 (e.g., outer coil 407) conductive traces 408a and 408f and provide an isolation barrier between the patient and the generator 200.

As shown in FIGS. 5-7, the inner vias 409b are arranged to form the inner circumferential region 302a of the coil 302 and the outer vias 409c form the outer circumferential region 302b of the coil 302. The inner and outer vias 409b and 409c pass through the layers 404b, 404c, and 404d. The inner vias 409b and outer vias 409c may be disposed in a concentric configuration. In a non-staggered configuration, corresponding inner and outer vias 409b and 409c lie along same rays. In a staggered configuration, the inner and outer vias 409b and 409c lie along alternating rays "r" as shown in FIGS. 5-7. The rays "r" are disposed at and an angle "a" relative to each other and the inner vias 409b are separated by a distance "d." Each of the inner vias 409b is connected to two neighboring outer vias 409c through traces 408b and 408e and vice versa. The interconnection of the vias 409b and 409c with the traces 408b and 408e forms a plurality of loops, which in turn, form the outer coil 407 as shown in FIG. 5.

The outer coil 407 may include any suitable number of turns, in embodiments from about 50 turns to about 100 turns. The maximum number of turns depends on the radius of the inner circumferential region 302a, via aspect ratio, thickness of the outer coil traces 407 and/or PCB 400, and spacing between the turns based on the limits of manufacturability of the PCB material (e.g., trace to trace, trace to via, via annular pad dimension, anything that may limit the placement of the conductors on the PCB).

With reference to FIGS. 6 and 8, the inner coil 405 is disposed within the outer coil 407 and also has a substantially circular shape. The inner coil 405 may include an upper trace 408c and a bottom trace 408d. The traces 408c and 408d are disposed over a dielectric layer 404c, such that the traces 408c and 408d are insulated from each other. The traces 408c and 408d may be electrically coupled to each other. In embodiments, the inner coil 405 may be formed from a single trace.

As shown in FIGS. 6 and 9, the coil 302 is coupled to the conditioning circuit 301 at a side connector 422, which may also be disposed on the PCB 400. The coil 302 includes a first terminal 410a coupled to the inner coil 405 and a second terminal 410b coupled to the outer coil 407. In particular, the outer coil 407 is disposed over the inner coil 405 and is coupled thereto. Thus, two terminals 410a and 410b are disposed at one end of the coil 302. The interconnection between the inner coil 405 and the outer coil 407 as well as the connection to the terminals 410a and 410b may be made through the vias 409b and 409c.

The controller 224 is provided to sensor signals from the sensor 300, which are then utilized to determine the current. Various formulas may be utilized by the controller 224 to determine the current. The voltage produced by the coil 302 may be calculated using the formula (I):

$$V_{OUT} = \frac{-A_{LOOP}N_{LOOPS}}{2\pi R_{COIL}}\mu_0 \frac{dI}{dt} \qquad (I)$$

In formula (I), A is the area of the turn (e.g., loop) formed by the vias 409b and 409c with the traces 408b and 408e, N is the number of turns, R is the major radius of the coil 302, to is the magnetic constant, dI/dt is the rate of change of the current being measured by the coil 302.

Inductance and capacitance of the coil may be calculated using the formulae (II)-(IV), respectively. Capacitance of the coil 302 is used to determine self-resonance and may be calculated using parallel-wire model formulae, namely, capacitances of inner and outer vias 409b and 409c and traces 408b and 408e.

$$L_{Coil} = \frac{\mu_0 \cdot N_{Turns}^2 \cdot t_{coil}}{2\pi} \ln\left(\frac{r_{coil\_inner} + w_{coil}}{r_{coil\_inner}}\right) \qquad (II)$$

$$C_{Coil} = N_{Turns} \cdot (2 \cdot C_{trace-trace} + C_{via-inner} + C_{via-outer}) \qquad (III)$$

$$C_\| = \frac{\pi \cdot \varepsilon_0 \cdot \varepsilon_r \cdot l_{trace/via}}{\ln\left(\frac{d_{between\_trace/via}}{2 \cdot r_{via/trace}} + \sqrt{\frac{d_{between\_trace/via}^2}{r_{via/trace}^2} - 1}\right)} \qquad (IV)$$

In formulae (II)-(IV), in addition to the variable and constants utilized in formula (I), t is thickness (e.g., distance between conductive traces 408b and 408e), r is radius, w is the radial distance between inner and outer circumferential regions 302a and 302b, Rcoil_inner is the radial distance to the inner circumferential region 302a, l is length, Co is vacuum permittivity constant, and ε_r is the relative dielectric constant of the PCB.

With reference to FIGS. 4 and 10-15, components of conditioning circuit 301 of the sensor 300 is shown. Since the coil 302 provides a differentiating response, the output must be integrated to provide the actual response through the conditioning circuit 301 of the sensor 300. The output of the coil 302 is integrated to produce a signal that is proportional to the current in the active lead 228a. The conditioning circuit 301 provides integration with the integrator 312. This allows for easy adjustability of the sensor gain, utilization in the control loop and processing by an analog-digital converter. Gain may be set by adjusting the frequency setpoint of the integrator 312. The setpoint may be achieved by selection of hardware component values (e.g., discrete resistor or capacitor substitution), selection of software values (e.g., digital or analog potentiometers or adjustable capacitors), including programmable gain amplifiers as described in detail below, or combinations thereof.

The gain amplifier 306 of the conditioning circuit 301 is shown in FIG. 10 and includes a pair of operational amplifiers 306a and 306b configured to provide differential gain without adding to the common-mode gain. The sensor signal from the coil 302 is provided to the positive terminals of the amplifiers 306a and 306b. The outputs of the amplifiers 306a are interconnected by a gain setting voltage divider network 306c including three resistors 306d, 306e, 306f. Terminal resistors 306d and 306f are coupled in parallel with capacitors 306g and 306h, respectively. The signal from the parallel circuits is coupled to the negative terminals of the amplifiers 306a and 306b, which provide closed-loop feed-

back thereto. Capacitors 306g and 306h provide amplifier stabilization and may also provide for the integration of the signal.

The output of each of the operational amplifiers 306a and 306b is provided to the differential to single-ended amplifier 308, which is shown in FIG. 11. In particular, the output of the amplifiers 306a and 306b is supplied to the positive and negative inputs of the amplifier 308. The amplifier 308 combines the output of the amplifiers 306a and 306b to provide a single output to the bandpass filter 310. The amplifier 308 includes a closed feedback circuit having a reference signal connected to ground including a resistor 308a, which is connected in series with a capacitor 308b that is coupled in parallel with a resistor 308c. The bandpass filter 310 includes a high-pass filter 309 and a low-pass filter 311 as shown in FIGS. 12 and 13, respectively. In embodiments, the output from the amplifier 308 may be passed through the high-pass filter 309 before being passed through the low-pass filter 311, or vice versa.

The high-pass filter 309 is configured to pass high frequencies and attenuate lower frequencies. The high-pass filter 309 includes an operational amplifier 309a. The output from the amplifier 308 is provided to the input of the amplifier 309a through a first capacitor 309b coupled in series with a second capacitor 309c and a first resistor 309d and a second resistor 309e. The negative input of the amplifier 309a is provided by a feedback loop from a third resistor 309f coupled in series with a grounded fourth resistor 309g.

The low-pass filter 311 is configured to pass low frequencies and attenuates higher frequencies. The low-pass filter 311 includes an operational amplifier 311a. The input from the high-pass filter 309 is provided to the input of the amplifier 311a through a first resistor 311b coupled in series with a second resistor 311c and a first capacitor 311d and a second capacitor 311e. The negative input of the amplifier 311a is provided by a feedback loop from a third resistor 311f coupled in series with a grounded fourth resistor 311g.

Since the voltage that is induced in the current sensor coil 302 is proportional to the rate of change of current that is flowing through the active lead 228a, the integrator 312 is utilized to provide an output signal that is proportional to the sensed current. In embodiments, a leaky integrator may be used. As used herein the term "leaky integrator" refers to an integrator having a low-pass filter as described in further detail below with respect to FIG. 14. The integrator 312 includes an amplifier 312a with a positive input thereof coupled to a ground. The input from the bandpass filter 310 is fed through a low-pass filter 312b, which includes a first resistor 312c coupled in series with a second resistor 312d that is coupled in parallel with a capacitor 312e. The second resistor 312d and the capacitor 312e are also coupled to the output of the amplifier 312a thereby providing a closed loop feedback thereto. The input signal is then fed to the negative input of the amplifier 312a.

The integrator 312 provides a negative slope of voltage gain verses frequency. This compensates, or flattens the opposite slope of the signal coming from the coil 302. Further, the integrator 312 has extremely high DC gain. The frequency band of interest for the generator 200 is well above DC. The integrator gain would create problems if a DC offset were present at its input. The high-pass portion of the band-pass filter 310 reduces the low frequency components and reduces any DC offset, which mitigates issues caused by the integrator's amplification of these components.

FIG. **15** shows a graph **500** illustrating individual gain response of the coil **302**, the integrator **312**, and the combined response of the coil **302** and the integrator **312**. The graph **500** shows the overall response of the coil **302** as a plot **502**, the response of the integrator **312** as a plot **504**, and the combined response of the coil **302** and the integrator **312** of the sensor **300** as a plot **506**, which is a combination of the plots **502** and **504**. Frequency, f1, is determined by the response of the integrator **312** and frequency, f2, is determined by the resonant frequency of the coil **302**.

With reference to FIGS. **16** and **17**, the active lead **228**a carries both common-mode (CM) and differential-mode (DM) current. For the purpose of measuring energy delivered to the patient, DM current can provide useful data. Thus, having a system and method of separating the DM current from the CM current in a conductor would then allow for more accurate sensors. In a single-conductor Rogowski coil, the CM current and DM current are indistinguishable from one another.

With continued reference to FIG. **17**, by adding a second conductor, namely, the return lead **228**b, and appropriately orienting the return lead **228**b through differential-mode RF current sensor **600** a signal as a function of the DM current. The relationship between the measured current and the sensor signal V_{signal} depends on the core being used in the RF current sensor.

As illustrated in FIG. **17**, the CM currents on the active lead **228**a and return lead **228**b pass through the center of the current sensor **600**, but in opposite directions. The flux produced by CM currents cancel each other out, and the current sensor **600** produces zero signal in proportion to the CM current. The DM currents pass through the current sensor **600** in the same direction due to the routing of the active lead **228**a and return lead **228**b, namely, looping of the return lead **228**b. The flux produced by DM currents are additive, and the current sensor **600** produces a signal that is based on the sum of (e.g., twice of) the DM current. If an iron or ferrite core is being used, then V_{signal} is proportional to the DM current, thus in FIG. **16**, V_{signal} is proportional to the sum of CM and DM currents and in FIG. **17** V_{signal} is proportional to the sum of only the DM currents. If an air core is being used, then V_{signal} is proportional to time rate of change of V_{signal}, thus in FIG. **16**, V_{signal} is proportional to a derivative of the sum of CM and DM currents and in FIG. **17** V_{signal} is proportional to the sum of time derivative of only the DM currents. Although the above-described embodiment is related to a Rogowski coil as a current sensor, the disclosed orientation of the active and return leads may be applied to any type of a current-sense transformer.

FIG. **18** shows a current sensor assembly **604** including the differential-mode RF current sensor **600** and a fully differential condition circuit **650** according to the present disclosure. The current sensor **600** includes a current sensor coil **602** and is shown schematically in FIG. **19**. The current sensor **600** is configured to measure individual first and second currents of active and return leads **228**a and **228**b or a net current. Current transformers are configured to measure either common-mode current or differential-mode current flow. In a typical application using power electronics, such as an inverter for generating alternating current, complex currents flow which have both differential and common-mode components which make up the totality of the flowing current.

The current flowing through each of the leads **228**a and **228**b generates a corresponding magnetic field within the current sensor **600**. The net magnetic field then affects the

current sensor **600**, which detects the differential-mode current. The embodiment of the current sensor coil **602** of FIG. **19** is configured as a differential-mode current sensor since it allows for use with multiple active and return leads **228**a, **228**b and **228**c, **228**d (FIG. **33**).

The current sensor **600** and the conditioning circuit **650** provide a completely differential signal, which provides better noise immunity. First and second terminals **612**a and **612**b of the current sensor coil **602** are coupled to the conditioning circuit **650**. Current sensor coil **602** also includes a third terminal **612**c as described in further detail below with respect to FIG. **26A**.

Each of the first and second terminals **612**a, **612**b is coupled to a differential integrator **637**, which includes a plurality of resistors **635**a, **635**b. The differential integrator **637** compensates for the derivative nature of the sensor signal from the current sensor coil **602** as described above with respect to the current sensor coil **302**. One or more of the resistors **635**a, **635**b may be coupled to differential gain switches (e.g., MOSFETs, analog switches, relays etc.) **636**a, **636**b, respectively. The switches **636**a, **636**b are configured to change the value of the resistors **635**a, **635**b, respectively, to adjust the gain of the conditioning circuit **650**.

The resistors **635**a, **635**b are coupled to input terminals of an amplifier **638**. The differential integrator **637** also includes capacitors **638**a, **638**b coupled to the amplifier **638**. The differential integrator **637** is, in turn, coupled to an active bandpass filter **640**, which also includes an amplifier **641** and associated circuit components. The bandpass filter **640** is then coupled to an analog-to-digital converter **642**, which then transmits the converted digital signal to the controller **224**.

FIG. **20** is a graph **700** of a gain response of the current sensor assembly **604** of FIG. **18** according to the present disclosure. The graph **700** shows individual and combined gain responses of the current sensor coil **602**, differential integrator **637**, and the bandpass filter **640**. The graph **700** shows the overall response of the current sensor coil **602** as a plot **702**, the response of the differential integrator **637** as a plot **704**, and the response of the bandpass filter **640** as a plot **706**. The graph **700** also shows the combined response of the current sensor coil **602**, differential integrator **637**, and the bandpass filter **640** as a plot **708**, which is a combination of the plots **702**, **704**, and **706**. Frequency, f1, is determined by the response of the differential integrator **637** and the bandpass filter **640**, and frequency, f2, is determined by the bandpass filter **640**.

In certain situations, the RF energy passing through the leads **228**a and **228**b may have relatively high voltage but low current. Undesired voltage signal from the leads **228**a and **228**b, which acts as primary conductors can couple to the current sensor coil **602**, which acts as a secondary winding, producing a significant error signal. The present disclosure provides for systems and methods for reducing the error signal due to voltage coupling between the active leads **228**a and **228**b and the current sensor coil **602**. In particular, the present disclosure provides for specific arrangement of the active and/or return leads **228**a, **228**b relative to the current sensor coil **602** such that the undesired voltage signal is coupled as a common-mode signal and is then cancelled or reduced by the common rejection capabilities of the conditioning circuit **650**. The present disclosure also provides for shielding the current sensor coil **602** to minimize coupling of the voltage signal. In embodiments, any combinations of arrangement of the active and/or return

leads 228a, 228b and/or shielding may be utilized to minimize coupling of the voltage signal.

With reference to FIGS. 21 and 22, the voltage coupling due to parasitic capacitance is described. FIGS. 21 and 22 illustrate the generator 200 including the RF amplifier 228 supplying RF current, Ip, through the active lead 228a with the current sensor coil 602 sensing the primary current, Ip, passing therethrough. The primary current, Ip, induces a secondary current, Is, in the current sensor coil 602, which develops a voltage, Vo.

In situations where the voltage at the active lead 228a is relatively large but the primary current, Ip, is low (e.g., near zero), the resulting Vo should also be near zero. With reference to FIG. 22, the high voltage capacitively couples from the active lead 228a to the current sensor coil 602, as represented schematically by a parasitic capacitance Cp1, which produces an erroneous output voltage.

FIG. 23 shows an embodiment of the present disclosure for reducing or eliminating erroneous output voltage signal output by the conditioning circuit 650. The present disclosure provides for a system of positioning the active leads 228a and/or return leads 228b in such a way as to balance the capacitive coupling therefrom to the current sensor coil 602. The conditioning circuit 650 then reduces the erroneous output voltage due to its common-mode rejection capability.

The active lead 228a is passed through the current sensor coil 602 to generate a second parasitic coupling capacitance, Cp2, which is also coupled to the current sensor coil 602. In particular, the capacitances Cp1 and Cp2 are coupled symmetrically about the sensor current sensor coil 602. The capacitance Cp2 couples a voltage from the active lead 228a to the current sensor coil 602 similarly to the capacitance Cp1, thereby balancing the circuit such that the resulting voltage is a common-mode voltage, which is then rejected by the conditioning circuit 650.

FIG. 24 shows another embodiment of the present disclosure for reducing or eliminating erroneous output voltage by the conditioning circuit 650. The current sensor 600 includes one or more shielding members 606 disposed between the active leads 228a and the current sensor coil 602 to prevent or reduce the voltage coupling from active lead 228a to current sensor coil 602.

FIGS. 25A-E show an embodiment of the current sensor 600 including a circular current sensor coil 602 disposed on a printed circuit board (PCB) 601, which may be formed using the techniques described above with respect to the current sensor coil 302 of FIGS. 5-9. The current sensor 600 includes one or more active leads 228a, 228c and return leads 228b, 228d passing through an opening 603 of the current sensor coil 602. The leads 228a, 228b, 228c, 228d may be any suitable conductive leads (e.g., wires) having an insulating sheath. In embodiments, the leads 228a, 228b, 228c, 228d may be printed as conductive traces on the PCB 601 and passed through the current sensor coil 602 as vias, such as traces 408a and 408f and via 409a as described above with respect to FIGS. 5 and 9.

The current sensor 600 also includes a pair of shielding members 606a and 606b disposed over upper and lower surfaces of the current sensor coil 602. With reference to FIG. 25E, the shielding member 606a is shown and described, which is substantially similar to the shielding member 606b. The shielding member 606a is formed from a conductive material and is coupled to a ground "g" as shown in FIG. 24. The shielding member 606a includes an opening 608 therethrough for passage of leads 228a, 228b, 228c, 228d. The shielding member 606a is configured and dimensioned to substantially cover the current sensor coil

602. Since the current sensor coil 602 is disposed on the PCB 601, the shielding members 606a and 606b may be substantially flat. The shielding member 606a may be a discrete conductive layer attached to the PCB 601 on which the current sensor coil 602 is disposed using any suitable fasteners, adhesives, and combinations thereof.

In embodiments, the shielding members 606a, 606b, may be formed as layers on the PCB 601 as shown in FIG. 25E. As a result, the PCB 601 may include additional dielectric layers (e.g., outer dielectric layers) to accommodate the shielding members 606a, 606b as integrated layers. The shielding members 606a, 606b may be printed as a conductive layer on the PCB 601 as described above with respect to the printing of the current sensor coil 302. This configuration may be used in embodiments in which the leads 228a, 228b, 228c, 228d are formed as vias and traces. In particular, an additional dielectric layer may be disposed on top of the conductive trace 408b (FIG. 8), on top of which the shielding member 606a is then formed, as well as below conductive trace 408e (FIG. 8), below which the shielding member 606b is then formed.

The current sensor 600 also includes a pair of opposing spacers 610a and 610b. The spacers 610a and 610b are formed from a dielectric material and when assembled define an opening therethrough which aligns with the opening 603 of the current sensor coil 602. The leads 228a, 228b, 228c, 228d are wrapped around and through the spacers 610a and 610b as shown in FIG. 25D to maintain the leads 228a, 228b, 228c, 228d in a predetermined spatial relationship relative to themselves and the current sensor coil 602 to cancel and/or reduce the effects of parasitic capacitance as described above. The current sensor 600 also includes a pair of opposing housing portions 630a, 630b enclosing the interior components of the current sensor 600. The housing portions 630a, 630b also secure leads 228a, 228b, 228c, 228d relative to each other and the current sensor coil 602.

With reference to FIGS. 26A-31C, embodiments of a single-wire orientation of the active lead 228a about the current sensor coil 602 are shown. The coil 602 includes forming an inner coil 605 and an outer coil 607. With specific reference to FIG. 26A, the current sensor coil 602 at a first end 609 includes two terminals 612a and 612b coupled to the outer coil 607 and the third terminal 612c coupled the inner coil 605. The third terminal 612C also couples the inner coil 605 to the ground at the first end 609. The inner coil 605 center taps the outer coil 607 at a second end 611 as described in further detail below with respect to FIGS. 26B and 26C.

With continued reference to FIG. 26A, the outer coil 607 includes a semi-circular first portion 607a and a semi-circular second portion 607b and the inner coil 605 includes a semi-circular first portion 605a and a semi-circular second portion 605b. The first and second portions 605a, 605b and 607a, 607b are disposed symmetrically (e.g., on left and right sides) about an axis "X-X" defined between diametrically opposed (e.g., 180° apart) first and second ends 609 and 611 of the current sensor coil 602, respectively.

With reference to FIGS. 26B and 26C, enlarged schematic views of the first and second ends 609 and 611 of the current sensor coil 602, respectively, are shown. The first portion 607a of the outer coil 607 is coupled between the first terminal 612a on top (e.g., at first end 609) and a first connection 611a of the first portion 605a of the inner coil 605 on the bottom (e.g., at second end 611). The second portion coil 607b of the outer coil 607 is coupled between the second terminal 612b on top (e.g., at first end 609) and a second connection 611b of the second portion 605b of the

inner coil **605** on bottom (e.g., at second end **611**). Each of the first and second portions **605***a*, **605***b* of the inner coil **605** is coupled between the third terminal **612***c* at the first end **609** of the current sensor coil **602** and their respective connections **611***a*, **611***b* at second end **611** of the current sensor coil **602**.

With reference to FIGS. **26**D-F, a top portion of the active lead **228***a* is passed across a top surface **602***a* of the current sensor coil **602** and is disposed in a −α orientation, e.g., at an angle α relative to the axis "X-X." A bottom portion of active lead **228** extends through the opening **603** and across a bottom surface **602***b* of the current sensor coil **602** such that the bottom portion of active lead **228***a* is disposed in a +α orientation relative to the axis "X-X." It should be appreciated that movement in the −α direction along sensor coil **602** in FIG. **26**D corresponds to movement in a downwardly direction along sensor coil **602** in FIG. **26**F. Similarly, movement in the +α direction along sensor coil **602** in FIG. **26**D corresponds to movement in an upwardly direction along sensor coil **602** in FIG. **26**F.

The active lead **228***a* is disposed symmetrically about the axis "X-X" across the top and bottom surfaces **602***a*, **602***b* of the current sensor coil **602** such that the erroneous voltage signals, Ve, generated by the active lead **228***a* are canceled out. In particular, the portion of the active lead **228***a* disposed on the top surface **602***a* and the portion of the active lead **228***a* disposed on the bottom surface **602***b* are symmetrical about the axis "X-X."

The top portion of active lead **228***a* creates capacitive coupling or parasitic capacitance C*t* within the sensor soil **602** at location L**1** (FIG. **26**F). Similarly, the bottom portion of active lead **228***a* creates capacitive coupling or parasitic capacitance C*b* within sensor coil **602** at location L**2** (FIG. **26**F). Two operating points identified as "P**1**" and "P**2**" in FIG. **26**E correspond to locations L**1** and L**2**, respectively, in FIG. **26**F. An error signal Ve is generated at location L**1** and an error signal Ve is created at location L**2**. The differential amplifier takes the difference of these two error signals to generate an output of zero (i.e., Vx=Ve–Ve=0). With the inner coil **605** attached at the center of the outer coil **607**, the capacitive coupling is balanced, causing the erroneous signal to be a common-mode voltage. Thus the differential circuitry causes the erroneous error signal to be removed. Accordingly, the embodiments of sensor circuit **602** provided above are balanced, have shielding, or are both balanced and have shielding such that the circuits produce little to no output signal Vx when there is no input current.

FIG. **26**E shows a plot **800** illustrating a logarithmic ratio of output voltage Vx of the amplifier to the voltage on active lead **228***a* vs. angular location. The logarithmic ratio is calculated using the equation of 20 Log(|V*x*|/|V*in*|), in which Vx is the output of the differential amplifier and V*in* is the voltage on active lead **228***a*. Operating points "P**1**" and "P**2**" correspond to the locations L**1** and L**2** of the parasitic capacitances C*t*, C*b* shown in FIG. **26**F. The slope of the graph illustrates sensitivity, i, of the output voltage Vx of the differential amplifier as a function of positional angle between the axis "X-X" and the active lead **228***a*. As the angle increases from about 0° to about 90°, the sensitivity to erroneous voltage signals Ve of the current sensor coil **602** decreases. This relationship may be used to locate the active lead **228***a* relative to the axis "X-X" to obtain the most accurate reading of the current passing therethrough while minimizing the interference caused by the erroneous voltage signals Ve.

With reference to FIGS. **27**A-B, **28**A-B, **29**A-C, **30**A-C, and **31**A-C, multiple embodiments of single wire configu-

rations of the sensor coil **602** are shown. With specific reference to FIGS. **27**A and **27**B, sensor coil **602** includes a length of wire, namely the inner coil **605**, passing through the middle of the sensor coil **602** such that the wire extends from a first end **609** to a second end **611** of sensor coil **602**. The top surface of sensor coil **602** in FIG. **27**A corresponds to the left side of sensor coil **602** in FIG. **27**B. Similarly, the bottom surface of sensor coil **602** in FIG. **27**A corresponds to the right side of sensor coil **602** in FIG. **27**B.

With respect to FIG. **28**A, sensor coil **602** is shown, differing from sensor coil **602** shown in FIG. **27**A by the addition of wire **228***a* running through the central opening in sensor coil **602**. Assuming there is no current traveling through the wire **228***a*, the output of the sensor coil **602** should be ideally zero. The wire **228***a* is in close proximity to the sensor coil **602** and will capacitively couple via C*t* an undesired error voltage, Ve, from the wire **228***a* to the sensor coil **602**. The position of wire **228***a* relative to the sensor coil **602** determines the location at which the error voltage is coupled, and thus affects how the circuit processes the signal. This, in turn, affects the output signal Vo.

FIGS. **29**A-C, FIGS. **30**A-C, and FIGS. **31**A-C show additional single-wire configurations of the sensor coil **602**. With specific reference to FIG. **29**A, the wire **228***a* is routed on the top and the bottom of sensor coil **602**. Thus, each of the top and bottom portions of wire **228***a* couples to the sensor coil **602** forming a parasitic capacitance C*t*, C*b*, as shown in FIG. **29**C. Since both C*t* and C*b* are at 0 degrees relative to the axis "X-X," they are capacitvely coupled to the center tap of the sensor coil **602**, which is grounded and therefore signal Ve is zero, hence, Vx is also zero. This corresponds to the operating points "P**1**" and "P**2**" shown in FIG. **29**B representative of a low error signal. Although this configuration provides for a low error signal, any movement in α yields a large change in error voltage.

FIG. **30**A shows both top and bottom portions of active lead **228***a* disposed in +α direction. As shown in FIG. **30**C, the top and bottom portions of active lead **228***a* are capacitively coupled at the same location due to the overlap of the active lead **228***a* on the sensor coil **602**, but off the center tap due to the placement of active lead **228***a* in FIG. **30**A as compared to the configuration shown in FIGS. **29**A-C. An error signal Ve, is coupled into the sensor coil **602** by each of the top and bottom portions of the active lead **228***a*. This corresponds to the operating points "P**1**" and "P**2**" shown in FIG. **30**B representative of error signal. The error signal is coupled to the negative input of the amplifier, and produces an output of Vx=−2Ve, since two active leads **228***a* are coupling to the same location.

FIG. **31**A shows the top and bottom portions of active lead **228***a* moved in the −α direction. The top and bottom portions of active lead **228***a* are capacitively coupled at the same location due to the overlap of the active lead **228***a* on the sensor coil **602**, but off the center tap due to the placement of active lead **228***a* in FIG. **31**A as compared to the configuration shown in FIGS. **29**A-C. An error signal Ve, is coupled into the sensor coil **602** by each of the top and bottom portions of the active lead **228***a*. This corresponds to the operating points "P**1**" and "P**2**" shown in FIG. **31**B representative of error signal. The error signal is coupled to the positive input of the amplifier, and produces an output of Vx=+2Ve, since two active leads **228***a* are coupling to the same location.

With reference to FIGS. **32**A and **32**B, a two-wire orientation of the active lead **228***a* and return lead **228***b* about the current sensor coil **602** is shown schematically. The active and return leads **228***a*, **228***b* are passed across the top surface

602*a* of the current sensor coil 602, through the opening 603, and across the bottom surface 602*b* of the current sensor coil 602. The top and bottom portions of the active lead 228*a* are symmetrical about the axis "X-X" at a first angle, −α and +α, respectively, and the top and bottom portions of the return lead 228*b* are symmetrical about the axis "X-X" at a second angle, +β and −β, respectively. The active and return leads 228*a*, 228*b* may be disposed at an angle ±α, ±β, respectively, from about 0° to about 90° relative to the axis "X-X." In embodiments, angles ±α, ±β may be the same, as shown in FIG. 32B, or different, as shown in FIG. 32A.

With reference to FIG. 33, multiple active leads 228*a* and 228*c* and multiple return leads 228*b* and 228*d* may be used depending on the number of outputs within the generator 200, e.g., bipolar, monopolar, etc. The active and return leads 228*a*, 228*c* and 228*b*, 228*d* are also disposed in a symmetrical relationship (e.g., transverse to the axis "X-X") relative to each other about the axis "X-X," such that the erroneous voltage signals are cancelled.

In embodiments, any number of active and return leads 228*a*, 228*c* and 228*b*, 228*d* may be wrapped about the current sensor coil 602 as illustrated in FIG. 33. This configuration may include two pairs of active and return leads 228*a*, 228*c*, and 228*b*, 228*d*, which may be disposed in an overlapping relationship, such that active and return leads 228*a*, 228*c* and 228*b*, 228*d*, respectively are disposed over each other. This arrangement may be used with a differential-mode current transformer configuration.

While several embodiments of the disclosure have been shown in the drawings and/or discussed herein, it is not intended that the disclosure be limited thereto, as it is intended that the disclosure be as broad in scope as the art will allow and that the specification be read likewise. Therefore, the above description should not be construed as limiting, but merely as exemplifications of particular embodiments. Those skilled in the art will envision other modifications within the scope and spirit of the claims appended hereto.

What is claimed is:

1. A sensor for sensing current, the sensor comprising:
a current sensor coil defining an opening therethrough and having a top surface and a bottom surface; and
an active lead passing through the opening of the current sensor coil, the active lead including:
a top portion extending parallel with and over the top surface of the current sensor coil at a first non-zero acute angle relative to an axis that extends through a first end of the current sensor coil and a center of the opening of the current sensor coil; and
a bottom portion extending parallel with and over the bottom surface of the current sensor coil at a second non-zero acute angle relative to the axis, the first non-zero acute angle and the second non-zero acute angle being symmetrical relative to each other about the axis.

2. The sensor according to claim 1, wherein the current sensor coil includes:
an outer coil;
a pair of first and second terminals coupled to the outer coil at the first end of the current sensor coil; and
an inner coil coupled to and disposed within the outer coil.

3. The sensor according to claim 2, wherein the current sensor coil is configured to output a differential signal indicative of a current within the at least one active lead.

4. The sensor according to claim 2, wherein the current sensor coil is disposed within a printed circuit board.

5. The sensor according to claim 4, wherein the current sensor coil further includes a shielding member disposed over the outer coil.

6. The sensor according to claim 5, wherein the printed circuit board includes:
a plurality of outer conductive traces each coupled to the active lead, the plurality of outer conductive traces being interconnected by at least one via through the printed circuit board.

7. The sensor according to claim 6, wherein the printed circuit board includes:
a top dielectric layer;
a first dielectric intermediate layer;
a bottom dielectric layer; and
a second dielectric intermediate layer.

8. The sensor according to claim 7, wherein the outer coil includes:
a plurality of top conductive traces disposed between the top dielectric layer and the first dielectric intermediate layer of the printed circuit board;
a plurality of bottom conductive traces disposed between the bottom dielectric layer and the second dielectric intermediate layer of the printed circuit board, wherein the plurality of outer conductive traces are disposed over an outer surface of the bottom dielectric layer and the top dielectric layer; and
a plurality of inner and outer vias interconnecting the pluralities of top conductive traces and the pluralities of bottom conductive traces.

9. The sensor according to claim 8, wherein the shielding member is disposed over an outer dielectric layer disposed over the outer surface of at least one of the top dielectric layer or the bottom dielectric layer.

10. The sensor according to claim 7, wherein the inner coil includes:
a conductive trace disposed within the outer coil and between the first and second dielectric intermediate layers of the printed circuit board.

11. The sensor according to claim 3, wherein each of the outer coil and the inner coil includes first and second portions, the first and second portions being separated at a second end of the current sensor coil, which is opposite the first end.

12. The sensor according to claim 11, further comprising:
a conditioning circuit configured to at least one of integrate, amplify, or filter the differential signal to output a processed signal indicative of the current of the differential signal.

13. The sensor according to claim 12, wherein the conditioning circuit is coupled to the first terminal and the second terminal, which are coupled to the first portion and the second portion of the outer coil, respectively, at the first end of the current sensor coil, and the first portion and the second portion of the inner coil are coupled to a third terminal at the first end of the current sensor coil.

14. The sensor according to claim 13, wherein the first portion of the outer coil and the first portion of the inner coil are coupled to each other at the second end and the second portion of the outer coil and the second portion of the inner coil are coupled to each other at the second end.

15. An electrosurgical generator, comprising:
a radio frequency output stage configured to output at least one radio frequency waveform;
a sensor including:
a current sensor coil defining an opening therethrough and having a top surface and a bottom surface; and

an active lead passing through the opening of the current sensor coil, the active lead including:

a top portion extending parallel with and over the top surface of the current sensor coil at a first non-zero acute angle relative to an axis that extends through a first end of the current sensor coil and a center of the opening of the current sensor coil; and

a bottom portion extending parallel with and over the bottom surface of the current sensor coil at a second non-zero acute angle relative to the axis, the first non-zero acute angle and the second non-zero acute angle being symmetrical relative to each other about the axis.

16. The electrosurgical generator according to claim 15, further comprising a return lead coupled to the radio frequency output stage and passing through the current sensor coil, wherein the current sensor coil is configured to output a second signal indicative of a current within the return lead.

17. The electrosurgical generator according to claim 15, wherein the current sensor coil includes:

an outer coil;

a pair of first and second terminals coupled to the outer coil at the first end of the current sensor coil; and

an inner coil coupled to and disposed within the outer coil.

18. The electrosurgical generator according to claim 17, wherein the current sensor coil is configured to output a differential signal indicative of a current within the active lead.

19. The electrosurgical generator according to claim 18, wherein the current sensor coil is disposed within a printed circuit board.

20. The electrosurgical generator according to claim 19, wherein the current sensor coil further includes a shielding member disposed over the outer coil and the printed circuit board includes a plurality of outer conductive traces each coupled to the active lead, the plurality of outer conductive traces being interconnected by at least one via through the printed circuit board.

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